Ref. Ares(2025)2889434 - 09/04/2025

Co-funded by the European Union

6GSNS

SUPERIOT

D1.4 Description of selected scenarios, applications, and their requirements (2)

Project number	**101096021**
Project name	**Truly Sustainable Printed Electronics-based IoT Combining Optical and Radio Wireless Technologies**
Project acronym	**SUPERIOT**
Call	**HORIZON-JU-SNS-2022**
Deliverable No	**D1.4**
Deliverable Name	**Description of selected scenarios, applications and their requirements (2)**
Status	**Final**
Dissemination level	**Public**
Due date of deliverable	**2023-10-31 (M10)**
Actual submission date	**2023-10-31 (M10)**
Resubmission date	**2024-12-20 (M24)**
Work package	**WP1 "Scenarios, Applications, Requirements, and Business Models"**
Lead beneficiary	**WAVECOM**
Authors	André Branquinho (editor), WAVECOM Konstantin Mikhaylov, UOULU Marcos Katz, UOULU Tuomas Paso, UOULU Hélder Fontes, INESC TEC Joana Tavares, INESC TEC Luís Pessoa, INESC TEC Nuno Almeida, INESC TEC Jakko Leppäniemi, VTT Emanuel Carlos, NOVA.id.FCT Joana Vaz Pinto, NOVA.id.FCT João Coelho, NOVA.id.FCT Guido Dolmans, IMEC-NL Utku Kumbul, IMEC-NL José Rabadán, LIGHTBEE SL

The SUPERIOT project has received funding from the Smart Networks and Services Joint Undertaking (SNS JU) under the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101096021, including top-up funding by UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding guarantee.

	Julio Rufo, LIGHTBEE SL Marcin Drzewiecki, MPICOSYS Pawel Musial, MPICOSYS Hazem Sallouha, KU Leuven Junaid Bocus, U of Bristol Kerstin Eder, U of Bristol
Reviewers	Konstantin Mikhaylov, UOULU José Rabadán, LIGHTBEE SL Julio Rufo, LIGHTBEE SL

Executive Summary

The goal of this document is to identify several promising applications and their basic requirements to serve as the initial project references needed to develop the SUPERIOT concept and its demonstrators. Three main scenarios are defined, namely 1) smart tags and labels, 2) large-scale sensing and actuation, and 3) enhanced IoT communication in demanding environments. The applications associated with each scenario are then described in detail and illustrated with examples. All the identified scenarios and applications are selected based on the premise that they can exploit the key capabilities of the SUPERIOT concept. Next, the general user requirements for the scenarios and their applications are defined. These user requirements are obtained by using mind maps tools. For each application, a requirement table is created containing information on a) the importance of each requirement to the application, b) the expected feasibility within the project framework, c) the expected timeline for the enabling technology maturity, and d) the demonstrators where the application could be possibly used. By analyzing the user requirement tables, a short list of the most appealing applications for the project is obtained, together with the most suitable project demonstrators for their implementation. Finally, more detailed requirements are defined based on the expectations of each demonstrator.

This deliverable was not initially contemplated in the project proposal. It was introduced in an Amendment as an extension to deliverable D1.1 to document the results of task T1.2 Determining Requirements for Selected Scenarios.

Table of contents

Editions

Version	Date	Modified by	Modification
0.1	2023-10-17	André Branquinho, WAVECOM	Draft for internal review
0.9	2023-10-30	André Branquinho, WAVECOM	Changes after internal review
1.0	2023-10-31	André Branquinho, WAVECOM	Final version for submission
1.1	2024-11-13	André Branquinho, WAVECOM	Added section 6.2 with preliminary studies on Bluetooth Low Energy Added sections to each demonstrator to address the selection of applications, taking into account the relevance to the project objectives/concept Included requirements regarding scalability, wireless range and IoT node density Revision on data rates and frequency of signaling requirements, access point density, and energy requirements
2.0	2024-12-20	André Branquinho, WAVECOM	Final version for resubmission

1 Acronyms

6G	The sixth-generation mobile communication system
AES	Advanced Encryption Standard
AP	Access Point
ATEX	Equipment for potentially explosive atmospheres
BLE	Bluetooth Low Energy
CNC	Computer numeric control
CPU	Central processing unit
DL	Downlink
EMC	Electromagnetic Compatibility
ER	Emergency room
ESL	Electronic shelf label
FPGA	Field programmable gate array
GPIO	General purpose input/output
GPS	Global Positioning System
GSM	Global System for Mobile Communications 2G
HAPS	High altitude platform station
HF	High frequency
ICT	Information and communication technologies
IoT	Internet of things
ITS	Intelligent transportation systems
LAN	Local area network
LDO	Low-dropout regulator
LED	Light-emitting diode
LiPo	Lithium polymer
LoS	Line of sight
LPWAN	Low-power wide area network

MCU	Microcontroller unit
MRI	Magnetic resonance imaging
NB	Narrow band
NB-IoT	Narrowband IoT
NFC	Near-field communication
NIR	Near infrared
OLED	Organic light-emitting diode
OPV	Organic photovoltaic
PCB	Printed circuit board
PD	Photodiode
PE	Printed electronics
PMU	Power management unit
PV	Photovoltaic
QoS	Quality of service
QR	Quick response
RF	Radio frequency
RFID	Radio-frequency identification
RIS	Reconfigurable intelligent surface
RX	Receive
Si	Silicon
Si-based	Silicon-based
SISO	Single-input single-output
SNR	Signal-to-noise ratio
SoC	System-on-a-Chip
SUPERIOT	Truly Sustainable Printed Electronics-based IoT Combining Optical and Radio Wireless Technologies
SWIPT	Simultaneous wireless information and power transfer
TX	Transmit

UAV	Unmanned aerial vehicle
UHF	Ultra-high frequency
UL	Uplink
UPH	Units per hour
UV	Ultraviolet
UWB	Ultra-wideband
V2V	Vehicle to vehicle
V2X	Vehicle to X
VLC	Visible light communication
WAN	Wide area network
WBAN	Wireless body area network
WPA	Wi-Fi Protected Access
WPAN	Wireless personal area network
WS	Workstations

2 Introduction

2.1 Motivation

The internet of things (IoT) is a communication paradigm where a network of physical objects with embedded functionalities (e.g., sensors, actuators, data processing) are connected to the internet. IoT can be seen as the ultimate connectivity frontier, where virtually any object can be connected. Thus, IoT can connect massively objects all around the globe. According to Cisco's recent forecast [1], up to hundreds of billion IoT devices will be connected during the 6G (the sixth-generation mobile communication system) era, generating an IoT market worth trillions of dollars. Considering the massive scale of this technology, it is evident that future IoT must be based on sustainable solutions. This has been the key driving force and goal of the SUPERIOT project. The project will develop and demonstrate the novel concept of truly sustainable IoT, where sustainability is approached in a holistic manner. Figure 1 depicts the main characteristic of the SUPERIOT project. **Multi-modality** in different domains (i.e., wireless connectivity, energy harvesting and positioning) as well as **reconfigurability** are the bases for a flexible and adaptable IoT system. Flexibility means that the same IoT solution can be used in different scenarios and applications, even when requirements of those are different. Adaptivity means that the IoT system can effectively react to the dynamic changes of the environment, e.g., changes in the communication channel conditions. The development of **sustainable implementation approaches of the IoT nodes** by exploiting printed electronics technology is another key aspect of the project.

The impact of IoT on our everyday life has been widely discussed, and its potential for improving our quality of life is undeniable. This is reflected by the countless existing IoT applications related to, among others, health (e.g., health monitoring, tracking of elderly people activities) [2][3][4][5], smart homes and buildings [6][7][8], security (e.g., physical access control) [9], environmental monitoring (e.g., monitoring of air quality, pollen, weather, etc.) [10], traffic (e.g., traffic flow management, etc.) [11][12], logistics (e.g., flexible and efficient use of resources) [13][14], and entertainment (e.g., environment-interactive smart games, connected devices, etc.) [15]. Furthermore, there are IoT applications that help using scarce and limited resources more efficiently, such as in the case of energy. The convergence of energy grids and IoT will allow efficient monitoring, analysis, and management of energy at small and large scale [16]. IoT is an essential component in the concept of smart city, where the use and optimization of public resources can be efficiently managed [17][18]. In addition, IoT is considered one of the keys enabling technologies of the Industry 4.0 paradigm [19][20]. IoT has also great potential for agriculture scenarios and applications [21][22][23]. These are just examples of possible IoT applications, and it is expected that new technologies such as the developed in SUPERIOT will not only further expand the application domain but also pave the way to exploiting IoT in novel and unexplored scenarios.

The goal of this deliverable is first to identify suitable scenarios and applications for the SUPERIOT concept, and second, to determine the basic requirements associated with these scenarios and applications. This initial work will allow the project to define in a later stage the key applications and their functional and technical specifications for which the four demonstrators will be developed. Even though each demonstrator will be developed and built around an application, this deliverable will also help identifying other possible scenarios and applications in which the demonstrator could also be used.

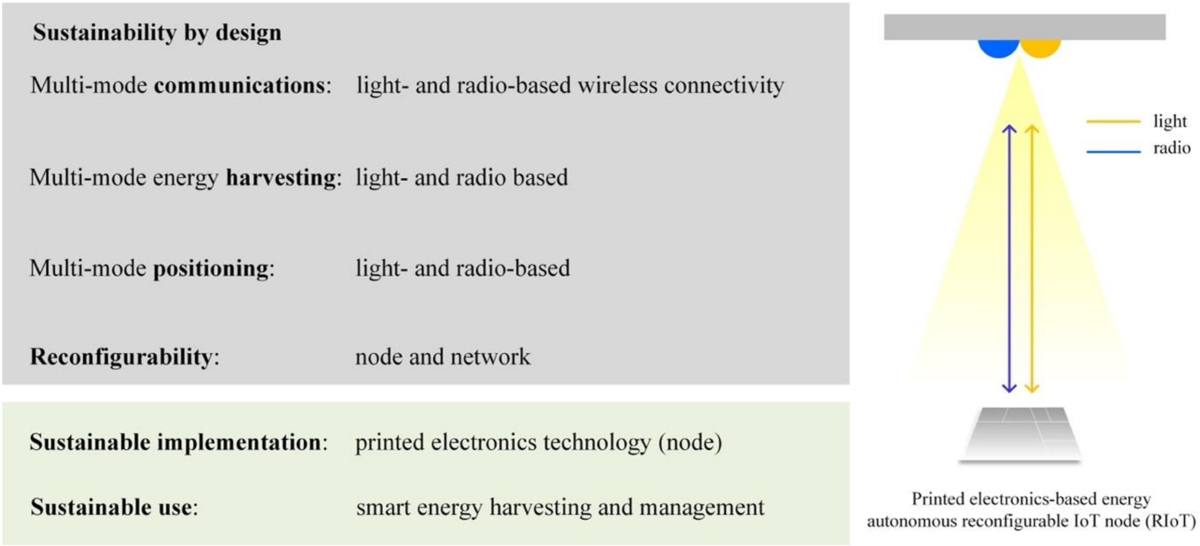


Figure 1. The key characteristics of the SUPERIOT concept.

2.2 Summary

This deliverable presents scenarios, applications, and corresponding requirements for SUPERIOT.

Initially, we describe the methodology used to gather possible applications and the grouping of these applications in three scenarios that represent a general vision of a future product or technology enhancement:

- SUPERIOT-SCN-1: smart tags and labels
- SUPERIOT-SCN-2: large-scale sensing and actuation
- SUPERIOT-SCN-3: enhanced IoT communication in demanding environments

The first scenario presents a vision of the tag/label of the future, taking advantage of the key concepts of SUPERIOT. The second scenario focuses on the possibility of creating smart and cost-efficient nodes that enable future large-scale sensing and actuation applications. Finally, scenario 3 explores how SUPERIOT can be used to improve IoT communication technology.

With the aim of evaluating feasibility of scenarios and applications, we derive an initial description of user requirements. Based on the expected feasibility and relevance of the applications, we evaluate the most interesting to include in the 4 demonstrators proposed in the project:

- Demonstrator 1: sustainable smart tag
- Demonstrator 2: advanced logistics in medical ICT (Information and Communication Technologies) scenarios
- Demonstrator 3: fully printed limited-capability IoT node
- Demonstrator 4: large-area IoT node

The different scenarios, applications and their relevance to the demonstrators presented in the first part of this document are based on Deliverable 1.1. The second part of this document updates the previous deliverable with the results obtained in Task 1.2. This new deliverable was not initially contemplated in the project proposal and should be considered as an update to the forementioned deliverable, making this new deliverable self-sufficient.

In this updated document, we go into more detail about the expectations of each demonstrator and define functional requirements for specific use cases. The functional requirements strongly depend on the use cases that the technology will serve in the future. Many SUPERIOT parameters are interdependent, which means that different use cases have different requirements for these parameters. Based on this assumption, the described use cases serve purely as examples to understand the ranges of values that may serve as guidance for the development of SUPERIOT.

The scenarios, applications and initial requirements presented in this document help the partners create a common vision for the technology that is going to be developed within the SUPERIOT project. Scenarios, applications, and corresponding requirements will be iteratively refined and revised throughout the lifetime of the project to ensure SUPERIOT is able to produce relevant and viable technology.

2.3 Structure of the document

The rest of the document is organized as follows. In Section 3, we present scenarios and applications for SUPERIOT. In each scenario, there is an overview explaining the vision and several possible applications are described. In Section 4, we explain the process that was followed to define the foreseen user requirements for each scenario. These requirements are then correlated with each application, identifying which requirements are relevant, their expectable feasibility, and their possible relation to the four proposed demonstrators. Section 5 identifies the most promising applications and their possible relation with the different demonstrators. The expectations of these demonstrators are described Section 6, together with some of the functional requirements derived with use case examples. Finally, Section 7 presents the discussion of the obtained results, the conclusion of the document, and future work.

Note that Sections 6.2, 6.3.4, 6.4.4, and 6.5.4 were introduced during the revision, addressing the comments and requests received. At the same time, modifications to other parts of the document were introduced, namely Section 6.6.1, and functional requirements Tables 33, 34, and 40.

3 SUPERIOT scenarios and applications

In this section, some of the foreseeable technological implementations within SUPERIOT concept are presented. A list of the project possible applications and scenarios has been organized based on the following definitions:

- Application: a possible current or future implementation of SUPERIOT technology to solve a specific challenge or to be applied in a certain environment where there is a benefit for the technology takers.
- Scenario: a vision of a SUPERIOT product or of a general technological concept that may be used to address different applications.

3.1 Methodology for gathering applications and scenarios definition

To be able to identify and define relevant applications and scenarios for SUPERIOT, we followed a set of steps that helped guide the discussions and decisions. The process is described in the following subsections.

3.1.1 Applications

The process for defining possible SUPERIOT applications started with a brainstorming session including all partners. This session had the following agenda:

- Context and goals
    - Explain the goals of the brainstorming session and how it is going to be conducted.
    - Recap and write the key technology points of SUPERIOT (those that should be leveraged in the applications).
- Generate ideas
    - Each participant writes their application ideas.
- Ideas presentation
    - Each participant shares their use case ideas.
    - Ideas are written in a shared document.
- Meeting summary and next steps
    - Check if some applications should be merged (e.g., similar applications with different benefits).
    - Try to group the applications (e.g., market groups, technology groups).
    - Review the results of the meeting and the shared document created.

The first step of this brainstorming session was to identify and summarize the key technology points of SUPERIOT, so that the ideas for applications would be based on the characteristics that should be leveraged in the project.

To gather the ideas from the participants, a form was used (Appendix 1). This form included the following necessary inputs for each application: simple name or designation to identify the application, the definition (what?), the benefit (why?), and the SUPERIOT advantages (technologies involved). An online version of the original form was used for registering more application ideas after the initial brainstorming session.

A shared document was then created with all the ideas and this document served as the basis for the following discussion sessions.

3.1.2 Scenarios

After the brainstorming session, possible technological scenarios were defined by identifying the similarities and eventual grouping strategies for the applications.

The first grouping strategy proposed for scenarios was based on the possible market vertical, namely: healthcare and safety, smart cities and buildings, vehicle communications, robot applications, and enhanced communication. However, this strategy led to scenarios that were hard to describe in terms of a product or technology vision. There were applications with very different purposes, where the only common point was the environment.

After this initial attempt, we opted for a technological vision approach, in which the scenarios group applications that solve similar challenges present in different market verticals. This approach proved to be more effective in terms of vision description and helped the process of discussing the necessary requirements.

This approach led to the establishment of three scenarios:

- Scenario 1: smart tags and labels
  - Future smart tags and labels for identification and traceability of objects (static or moving) and people, with enhanced functionality when compared to barcodes, quick response (QR) codes or even radio-frequency identification (RFID) labels.
- Scenario 2: large-scale sensing and actuation
  - Sustainable and inexpensive devices that can be deployed in large scale for environment sensing and actuation. These devices communicate relevant parameters to the network and are also able to act in the environment.
- Scenario 3: enhanced IoT communication
  - Technology developments that may be used to improve many types of applications. This scenario serves as a future technology platform to enhance IoT communication capabilities in general.

We note that although the above proposed classification based on applications associated with scenarios serving verticals define three logical scenario groups, there is not always a clear-cut classification of the applications as belonging to a particular scenario. In other words, some applications could belong also to a different scenario than the used in the classification, and moreover, some applications could be eventually combined, as discussed below.

The different scenarios and corresponding applications are described in the three following sections.

3.2 SUPERIOT-SCN-1: smart tags and labels

3.2.1 Scenario overview

This scenario focuses on future smart tags and labels that can be used to identify and track moving objects and people, with enhanced functionality when compared to the traditional barcode, QR codes or RFID labels. Besides their main purpose of identifying and tracking, these tags/labels could be equipped with sensing and actuation capabilities relevant to the objects and people they are tagging. These smart tags and labels would be in communication with a network, making the objects and people IoT nodes. These devices would take advantage of the key concepts of SUPERIOT, namely printed electronics, cost-effective production, radio frequency (RF)/visible light communication (VLC) and localization, and energy harvesting while being truly sustainable.

For some applications, these smart tags and labels could also be remotely reconfigurable, with updated information based on the context or on the measurement of relevant parameters, such as temperature, humidity, among others. Printed displays (readable information), along with efficient communication and localization capabilities could also enhance the applicability and handling of these tags. Finally, the design of autonomous, reusable, repurposable and flexible devices enables the development of new applications, ranging from wildlife monitoring and critical items tracking to anti-counterfeiting methods.

The applications inside this scenario focus mostly on the identification and traceability of people and goods, which means that there is typically a one-to-one ratio: one tag/label for each object or person. Moreover, the need of identifying and tracking is strongly related with the fact that these objects/people are not always static and can move through different zones and facilities, therefore both static and moving objects/people are considered in this scenario.

3.2.2 Applications

With these SUPERIOT smart tags and labels, several applications can be developed or enhanced, namely:

- SUPERIOT Application 1.1 - Smart labels attached or incorporated in day-to-day market products
  - These smart labels could be attached to day-to-day market products, as stickers, making it possible to monitor their quality in real-time. Modification of prices or expiry dates, based on the environment or other conditions that affect the product could also be implemented. This would help increase consumers' safety and experience by having this information updated in the printable display. Moreover, accurate localization would help in handling procedures, both in stores and in logistics.
- SUPERIOT Application 1.2 - Smart tags incorporated in sensitive items (high-value, high-risk, among others)
  - Printable unique tags could be incorporated in sensitive items during production, such as in-mold electronics, avoiding item counterfeiting and all the resulting issues for producers and end customers.
- SUPERIOT Application 1.3 - Tags and labels specifically designed for food and medicines
  - These disposable tags/labels would be able to detect opening and remaining content, enabling alerts when the food/medicine has expired the consumption period after opening or when medicine is running out. These tags/labels could also receive communications from the infrastructure when there is a batch recall, showing readable information and avoiding problems for the consumers.
- SUPERIOT Application 1.4 - Labels specifically designed for logistic operations
  - Autonomous disposable/reusable labels that identify goods or containers, and contribute to their traceability. These labels can localize them and detect relevant events in the supply-chain that may compromise the quality of the goods, such as: cold-chain monitoring, collision detection, or other harsh conditions. These tags may also be used as next generation luggage tags that can avoid handling errors in airports or other situations where item identification and localization is critical.
- SUPERIOT Application 1.5 - Enhanced labels for batch manufacturing
  - Autonomous labels placed on production carts or production bins that can be used to track batches during production, but also update the display to show relevant information about the current batch being transported. High-accuracy localization would help operators handle the batches, making the manufacturing process a lot more optimized.
- SUPERIOT Application 1.6 - Tags incorporated in shelves or in other small product packages

  - These tags could help warehouse or shop management, by knowing exactly the number and type of products on each shelf or box, using for example a pressure sensor. The tags could communicate the data to have accurate inventory in real-time, automate restocking, etc.

- SUPERIOT Application 1.7 - Tags and labels for healthcare patients
  - The SUPERIOT tags/labels could help solve some of the issues that healthcare units face every day. Even though there are already solutions for patient tracking inside the hospital, they involve non-disposable expensive tags. There is no good solution for situations where reusage of tags is not an option or in situations where there is a need for advanced information (e.g., localization inside the emergency room or remote monitoring of patients). The existent reusable tags/labels are not a viable option. The SUPERIOT tag/label with additional healthcare monitoring sensors could be incorporated, for example, in triage bracelets, enabling constant monitoring of patients, avoiding critical situations, and improving process efficiency.
- SUPERIOT Application 1.8 - Tags for smart pills
  - In the future, SUPERIOT tags could be incorporated in pills. These pills would have then the capability of communicating when swallowed. This would help ensure patients (e.g., psychiatric) take their medicines, and alert overdose or wrong medicine intake.
- SUPERIOT Applications 1.9 - Labels for tracking critical equipment
  - Critical equipment, such as medical devices and large factory production equipment, need periodic maintenance and audits. Searching through the facilities for a specific device that needs maintenance/audit is particularly cumbersome when there are hundreds or thousands of devices that are exactly the same (e.g., infusion pumps). A SUPERIOT cheap and autonomous label could be used to track each device, taking advantage of radio and light communication to have the necessary accuracy in different situations. The printable display or indicator could give updated information about the time left for maintenance, or other important contents.
- SUPERIOT Applications 1.10 - Tags for animal monitoring and management (livestock and wildlife)
  - Printed battery-less IoT nodes could be extremely small and light, resulting in an attractive solution to monitor and manage animals, including wild and farmed animals. The use of light could in principle also allow the use of such IoT nodes on fish.
- SUPERIOT Application 1.11 - Tags to increase collectible cards gaming experience
  - SUPERIOT could enable the future version of collectible cards (basketball, Pokémon Go, etc.) with smart functionality not available today. While maintaining a battery-free and environmentally friendly approach, these collectible cards could change game data from any light communication source. Cards could even directly communicate between them via directed light between specific gamers in larger groups, making games more interesting and dynamic.

3.2.3 Illustrative examples

To better illustrate the possible applications for SUPERIOT smart tags and labels, some images are shown below.

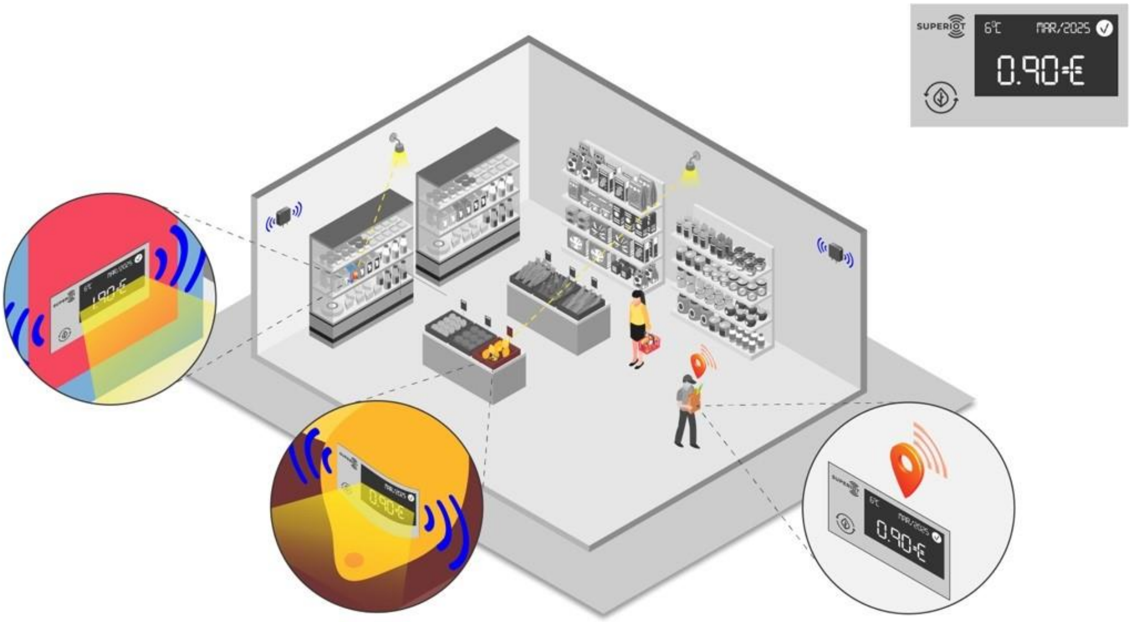


Figure 2. Scenario 1: smart tags and labels on day-to-day market products.

Figure 2 depicts examples of sustainable smart tags and labels used on day-to-day market products. As mentioned in SUPERIOT Application 1.1, these labels could monitor the location and quality of products in real-time, and dynamically communicate over light and radio. Incorporated display could be used to give information about expiry dates, temperature, etc.

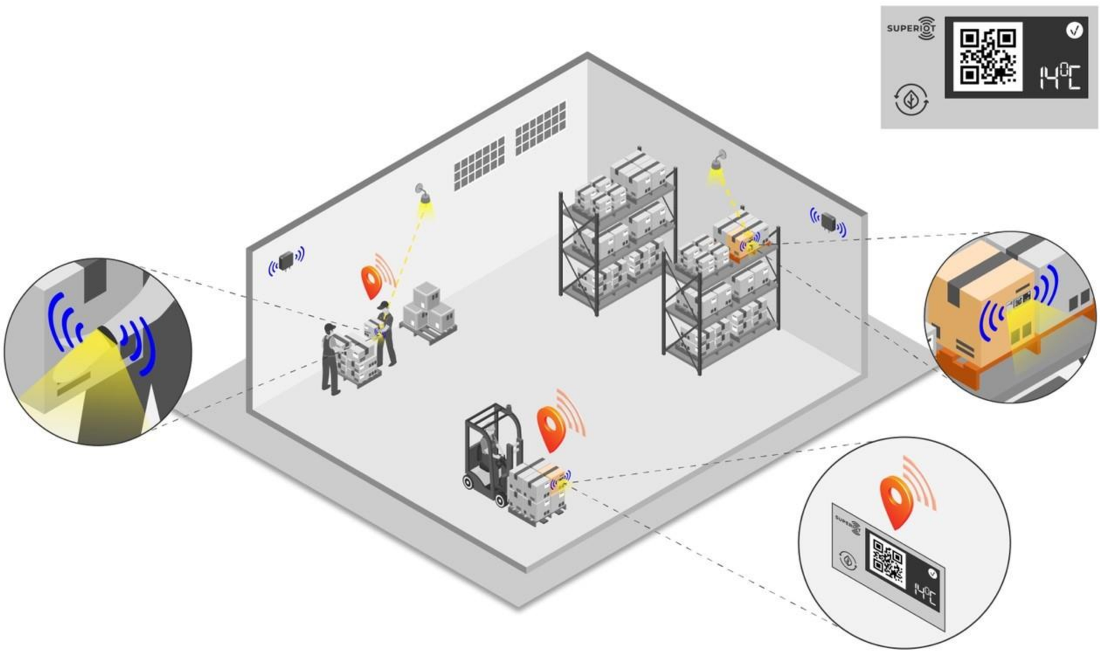


Figure 3. Scenario 1: smart tags and labels in logistic operations.

In Figure 3 the logistic operations using smart tags and labels are illustrated (SUPERIOT Application 1.4). Besides identifying items, they would be used to localize them using dual-mode communication. Cold-chain monitoring and automation of operations are other relevant benefits.

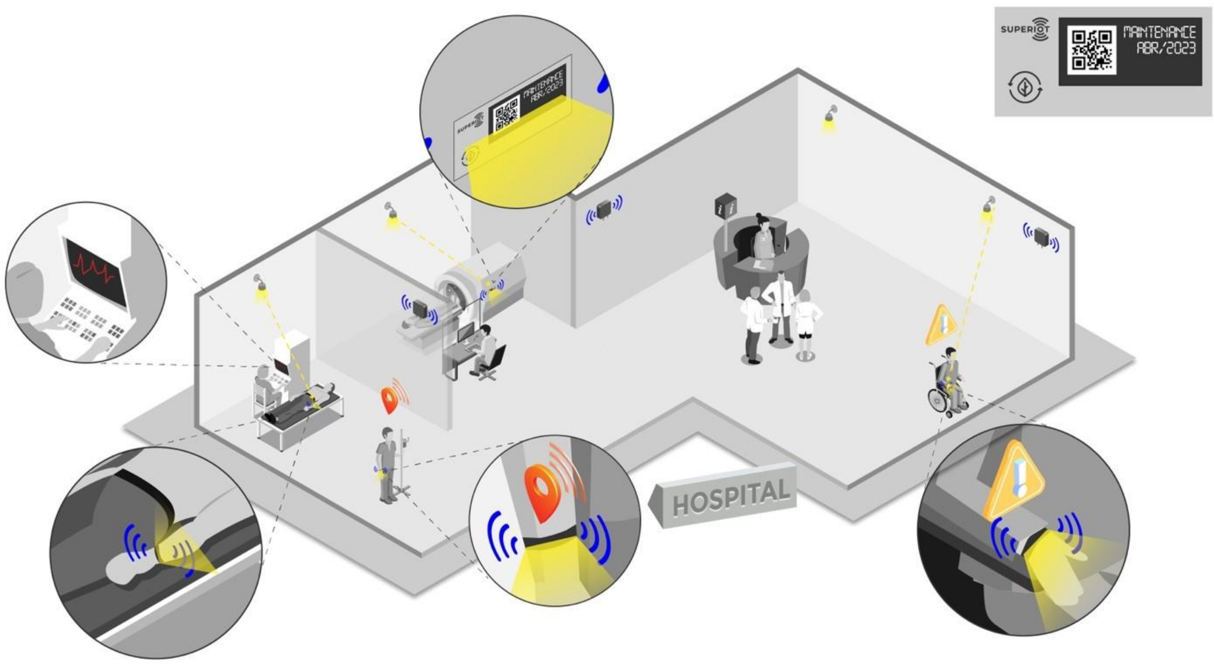


Figure 4. Scenario 1: smart tags and labels for healthcare patients.

Figure 4 represents part of a hospital where smart tags and labels are being used. The real-time location of patients is being monitored with disposable and eco-friendly bracelets (SUPERIOT Application 1.7). Critical equipment is also identified, and relevant information is shown in the smart label (SUPERIOT Application 1.9).

Figure 5. Scenario 1: smart tags and labels for animal monitoring and management.

Finally, Figure 5 shows an agriculture environment where animals are being monitored and managed using smart tags and labels (SUPERIOT Application 1.10). The dual-mode communication and reconfigurability enables sending and receiving data in challenging environments (such as underwater).

3.3 SUPERIOT-SCN-2: large-scale sensing and actuation

3.3.1 Scenario overview

SUPERIOT technology characteristics, such as printed electronics, VLC/RF communication, and energy harvesting, could enable the efficient production of small and flexible autonomous device capable of communicating in different environments. In this sense, IoT sustainable and inexpensive devices could be used to monitor the state of different systems on a large scale, even systems distributed across large areas. Systems here include forests biodiversity, environmental state, smart cities, agriculture, mining, among others. Additionally, the production of these devices could create opportunities for non-structured communication, enabling for example swarm operations.

Finally, in some scenarios, this sensing could be complemented with massive actuation, an interesting approach, particularly for printed IoT devices. Indeed, a node could also contain different means to locally actuate and eventually produce some changes in the environment where the node is inserted in. The network could control this actuation in response to some sensed information gathered from the node's local sensor and several distributed elements within the network.

The applications inside this scenario focus on the large-scale sensing and actuation in the environment, buildings, among others. This means that there is typically a many-to-one ratio: many sensing and actuation devices for each environment, building or even objects and people. These nodes communicate relevant sensing parameters to the network and possibly receive information on actions to perform in the environment.

3.3.2 Applications

The deployment of massive sensors and actuators could create the following application opportunities:

- SUPERIOT Application 2.1 - Sensors and actuators for smart buildings
  - Sustainable and inexpensive IoT devices could enable monitoring and actuation inside buildings on a large scale. This may include light intensity detection, temperature and humidity, electrical consumption monitoring, and even actuators that can act based on the gathered data. The increase in the number of deployed nodes would enable better monitoring, which is very difficult to attain with the currently available devices. With printed electronics and VLC/RF communication, the security and privacy in wireless access control systems could also be enhanced, avoiding battery waste at the same time thanks to the scavenging strategies from light and RF mainly that can be implemented with printed electronics devices. The safety inside buildings could also be increased with safety zones delimited by light, by enabling human eye identification, but also by communicating with sensors incorporated in smart workwear. Smart certificates could also be incorporated into equipment, making it possible for equipment to alert users when certificates are running out, or even to switch off when they run out. These devices are also relevant to enable pre-emptive maintenance, thus becoming a possible interesting component of industry 4.0.
- SUPERIOT Application 2.2 - Sensors and actuators for construction monitoring
  - The possibility for easy deployment of a large number of sustainable sensors that can measure forces, and humidity, among other parameters, and can communicate efficiently in different environments may help to monitor and communicate the status of buildings, or other structures (e.g., bridges, historical monuments, etc.). This could help avoid accidents and could help decrease the

maintenance costs in remote constructions. This sensorization could even be done during the construction process to guarantee that each step is correctly done before proceeding to the next one (e.g., concrete being dry enough), or even to generate automatic documentation of the construction. This could also be used to increase construction quality and reduce insurance costs.

- SUPERIOT Application 2.3 - Sensors for medical and safety applications
    - Inexpensive radiation dosimeters or other monitoring sensors could be used to increase staff and patient safety. With printed electronics, these sensors could be incorporated into clothes or other wearables and produced with safe materials that do not interfere with medical equipment. Other medical applications include the possibility of creating medical sensors that can be attached as patches or integrated into clothing and can autonomously perform medical tests (e.g., blood tests, etc.). This could improve patient safety by sending immediate reports of the patient's status.
- SUPERIOT Application 2.4 - Sensors and actuators applied to smart cities
    - The cost-efficiency and sustainability proposed in SUPERIOT could help massify the deployment of (printed) displays, and the VLC/RF communication could be used to give real-time information to users in many different scenarios. This may include traffic information, transport information (bus stops, airports, railway stations), but also more futuristic applications, such as unexpensive indoor flexible maps that can dynamically update the location of the user and other relevant information: opening of stalls, maintenance breaks, hazardous areas, etc. Visibility to people in darkness could also be provided by SUPERIOT technology, using light "reflectors" installed in fixed positions or embedded in clothing that can emit light and/or radio signals.
- SUPERIOT Application 2.5 - Sensors and actuators applied to smart agriculture and forestry
    - SUPERIOT sensors and actuators may find applications in forestry, agriculture, and animal management applications. IoT nodes could help to nurture and protect plants and trees by intelligently releasing fertilizers, drugs against plant diseases, or even fragrances to attract/repel insects. Another interesting topic is the possibility of using them for forest fire prevention by warning a centralized unit or even releasing substances that could help delay the fire propagation. These IoT nodes could also be used to create controlled soundwaves based on local tiny loudspeakers, making warning or scaring sounds. These sounds can be used to scare birds in cultivated fields, inhibit people from accessing protected areas, etc. The possible remote communication with actuators could also be used to create locally stimulating electrical signals, mechanical vibrations, or lights of a given wavelength, helping animal management, both livestock, and wildlife.

3.3.3 Illustrative examples

Some of the possible applications are depicted in the following images.

Figure 6. Scenario 2: large-scale sensing and actuation for smart buildings.

Figure 6 illustrates large-scale sensing and actuation for smart buildings (SUPERIOT Application 2.1) with cost-efficient printable nodes. These nodes, attached to walls or other surfaces, could monitor temperature, humidity, light intensity detection, or other relevant conditions. Actuation could be added to the nodes, making it possible to switch equipment based on the current conditions. This is represented by the actuation on the air conditioning. Dual light-radio communications, energy harvesting and reconfigurability are key concepts of this scenario.

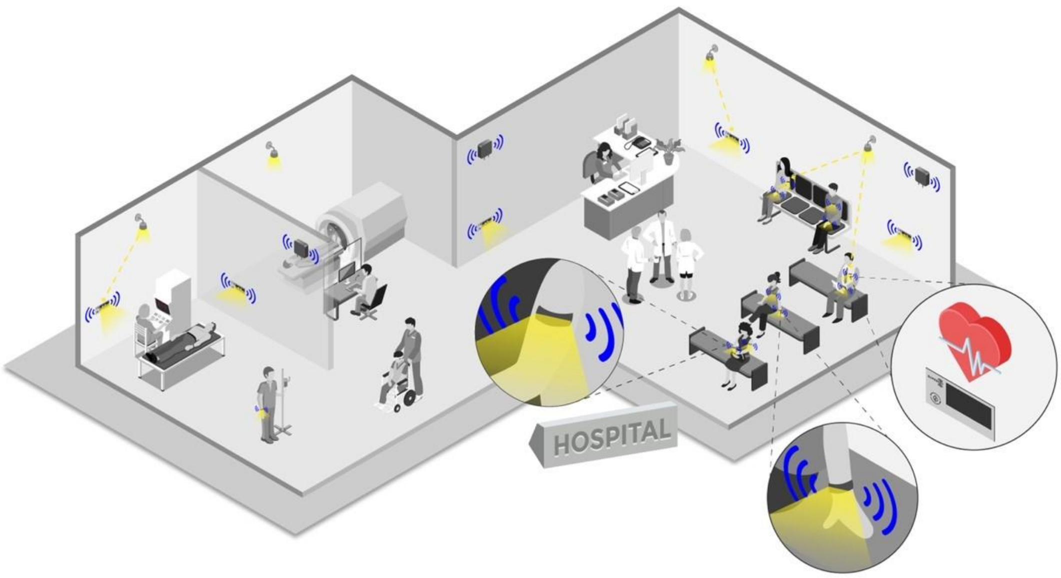


Figure 7. Scenario 2: large-scale sensing and actuation inside a hospital.

In Figure 7 the same principle is applied to a healthcare facility. Besides monitoring the building, nodes could be used as patches on patients, monitoring their condition and helping increase safety (SUPERIOT Application 2.3).

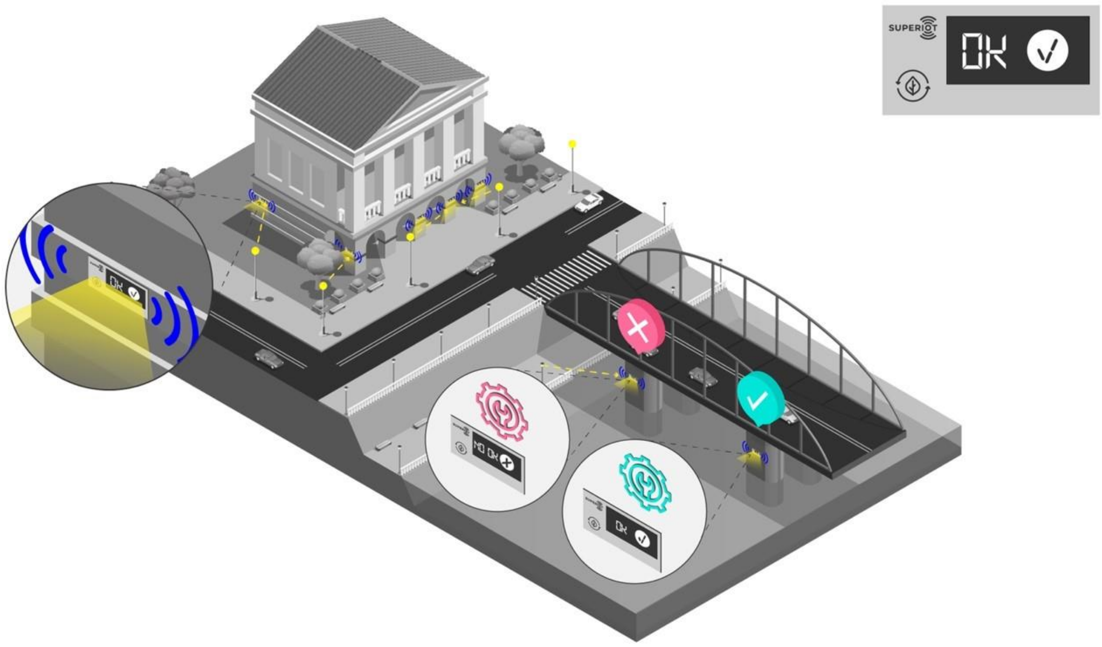


Figure 8. Scenario 2: large-scale sensing and actuation for construction monitoring.

Figure 8 shows a historical building and a bridge being constantly monitored to assess the construction quality and the need for maintenance, as described in application 2.2. With these SUPERIOT autonomous nodes, sensing could be easily deployed in a large scale.

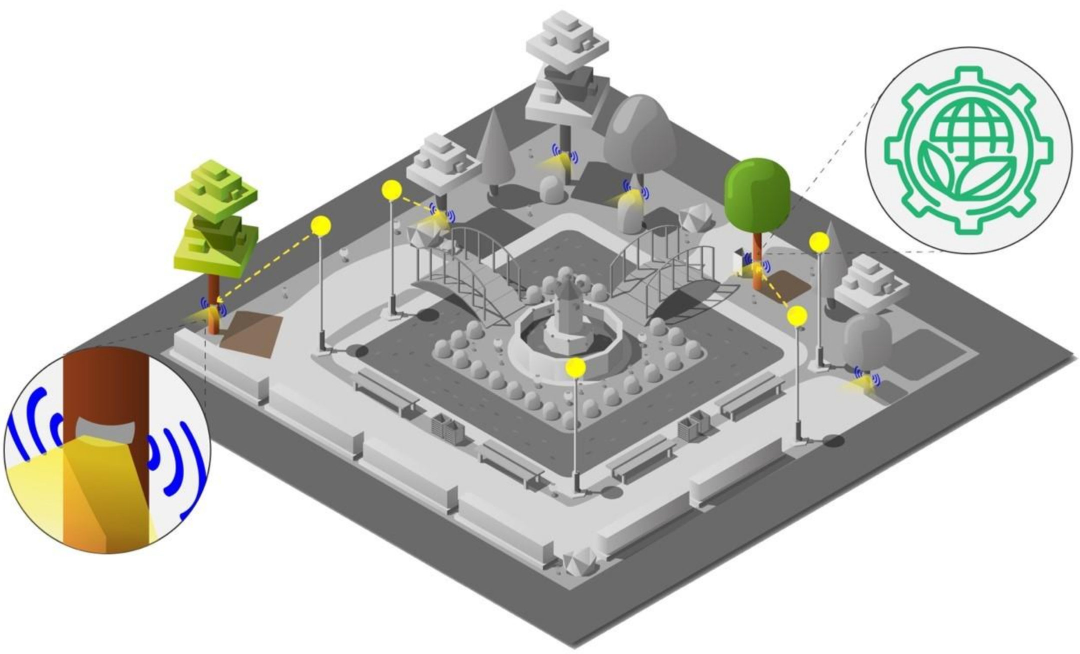


Figure 9. Scenario 2: large-scale sensing and actuation in forestry.

In Figure 9 trees are being monitored with the eco-friendly SUPERIOT nodes. Actuation capabilities of nodes could help to nurture and protect plants and trees by intelligently releasing fertilizers, drugs against plant diseases, or even fragrances to attract/repel insects (SUPERIOT Application 2.5).

3.4 SUPERIOT-SCN-3: enhanced IoT communication in demanding environments

3.4.1 Scenario overview

One of the key concepts of SUPERIOT is the possibility of having reconfigurable optical-radio IoT nodes and networks. This scenario explores applications where the adaptability and flexibility brought by the reconfigurable optical-radio concept could be used to improve IoT communication. The idea is that some future IoT applications will occur in highly demanding environments, i.e., military, mining, underwater, healthcare, explosive atmospheres (e.g., equipment for potentially explosive atmospheres, ATEX), etc. These environments require much more reliable, private, and secure communication. Localization using light and radio could be also an additional benefit in these types of environments.

Even when the environment is not critical, there are many situations where there are coverage issues, either by propagation difficulties or by having problems deploying communication infrastructure (underwater environment, for example). In this sense, printed electronics could also play an important role with nodes and network elements that are cost-effective and very easy to deploy and maintain.

Several applications will be described next. We note that the applications described in this scenario should be regarded as technology developments that may be used to improve many types of applications. This scenario serves as a future technology platform to enhance IoT communication capabilities in general.

3.4.2 Applications

The enhancement in IoT communications provided by SUPERIOT could be used in many different situations:

- SUPERIOT Application 3.1 - Secure and private IoT communication
    - In many situations, secure and private communications are of utmost importance and therefore particular care needs to be taken to design a secure communication system. Examples of environments where secure and private communications are required include healthcare, industrial floors, aircraft, military, enterprises, logistics, and others. Radio communication is typically more vulnerable to eavesdropping or planned attacks as radio waves typically propagate through walls and in general one cannot easily control the range of a radio communication system. Optical wireless communication is inherently more secure, and the optical signal typically remains confined in the room where the service is being provided. Considering the simplicity of IoT systems in general and the typical limitations of the IoT node/device in terms of complexity and energy limitations, it is a challenge to implement advanced security mechanisms in IoT systems. Combining optical and radio communications is highly advantageous, as their advantages are combined. A hybrid communication system like the one in the SUPERIOT concept can be used to create a secure communications system. Different strategies can be used to enhance security, such as a) maximizing the use of optical links, b) transmitting information coded or multiplexed across the radio and optical channels, c) transmitting sensitive information through secure channels (e.g., channels associated with optical communication), d) transmitting access keys through secure channels. Note that strategies providing security against unintended third parties (e.g., hackers) are also effective in creating a secure communication system from the point of view of electromagnetic interference. Maximizing the use of optical communications reduces the risk of creating

interference to, or being interfered with by, other equipment. Many of the aforementioned cases are also sensitive to electromagnetic interference. Interference-free operation in dense communication environments, or in situations where there is sensitive equipment or risk of explosion, can be provided by the SUPERIOT concept.

- SUPERIOT Application 3.2 - Reliable IoT communication
  - Certain services require dependability, that is, information needs to be delivered reliably to the destination. As wireless channel conditions may dynamically change with time, providing trustworthy information to the receiver could be challenging. Diversity is the most efficient approach to create reliable wireless links, and time-domain diversity (e.g., conventional coding) is the most used approach in communication systems. Advanced coding mechanisms could provide very effective protection against the dynamics of the channel, interference, and other impairments, though their complexity could be prohibitively high, particularly for an IoT system. SUPERIOT exploits connectivity diversity, as the system can be configured as a dual communication system based on optical and radio communications. Since propagation through the optical and radio channels present different characteristics and physical behavior, the channels are largely uncorrelated, and diversity can be effective if both radio and optical communication approaches are combined. The SUPERIOT concept can be exploited to create a reliable communication system by using, for example, the following strategies, a) transmitting simultaneously the same information over the radio and optical links and combining the received signals at the receiver; b) selecting a single transmission link based on the best associated channel (e.g., optical or radio). Critical environments where reliable communications are important include healthcare, industry, military, and vehicular, among others.
- SUPERIOT Application 3.3 - Underwater IoT communication
  - There are important situations where nodes and networks could be located underwater, either totally or partially. In general, we identify them as underwater applications. In some industrial environments, there could be other liquids than water. In practice, there is a great deal of underwater applications, including a) military; b) underwater ecosystem monitoring; c) sports; d) entertainment; e) industrial; f) water quality monitoring (natural water source -groundwater, thermal water-, swimming pools, aquariums, water treatment systems); g) underwater structure monitoring; h) fish monitoring (natural habitat, growing tanks). Radio communication is quite challenging underwater or in other environments where there are liquids involved (chemical industry, etc.). In these situations, a combination of radio and optical communications may be used to improve the quality of the communications. One possible idea for SUPERIOT would be to design IoT nodes meant to be used underwater or right on the surface. In the latter case, the node could provide connectivity through light below the surface, and radio above the surface. Printed electronics would be a very interesting concept for these use cases since they could help create nodes that are autonomous, environmentally friendly, and can be easily adapted to a liquid environment. These possibilities would have an interesting impact on military applications, ecosystem/wildlife monitoring, and other industrial environments.
- SUPERIOT Application 3.4 - In-body and on-body communication
  - Another relevant application defines cases where IoT devices could be located either inside the human body or right on the body (e.g., on the skin). These cases are related to healthcare applications, as other already described environments, but included here as a separate entry, as these cases lead to solutions that are substantially different to those in previously discussed applications. Applications include a) wireless connectivity to in-body devices such as electronic implants, sensors, actuators, and smart pills; b) brain-computer interfaces; and c) wireless

body area networks (WBAN). The mentioned applications exploit radio communications for connectivity and are critical in terms of security and privacy, therefore in principle the same challenges and solutions as discussed in Application 3.1 apply here. However, in these cases there are some important differences. First, in most cases, the typical connectivity ranges are from some millimeters to a few tens of centimeters. Also, the use of optical communications through biological tissues, a subject not widely studied, requires different light wavelengths than conventional over-the-air optical communications. The deepest optical signal penetration in bio tissues is achieved when near infrared (NIR) light is used. Using this type of light also maximizes security (e.g., eavesdropping, attacks, interference) as well as safety (e.g., exposure to electromagnetic radiation). However, light and radio communications can also be combined in these cases, as explained in applications 3.1 and 3.2. When the IoT device is on-body, connecting to in-body devices would typically be based on optical communications and connecting to other nodes or access points (APs) could be done using radio and/or optical communications.

- SUPERIOT Application 3.5 - Coverage extension with large-area IoT nodes
    - In this application, IoT nodes or related supporting devices could be used to provide coverage extension. Printed electronics could be used to create autonomous sticker-like network nodes and repeaters or reconfigurable intelligent surfaces (RIS). This would help improve the quality of IoT communications in situations where there is not enough network coverage. These nodes could be attached to walls to enhance communication capabilities and localization accuracy inside a room. The battery-less operation and completely wireless operation would strongly decrease the costs of setting up a communication or localization network. The dual optical-radio communication could also be used to create the concept of a smart window that would use radio to communicate with the outdoor systems and light to communicate with the indoor systems, making communication not only more reliable but also more private and secure. Also, the possibility of supporting device-to-device communication makes it possible to create ad hoc networks. The use of additional devices or advanced network configurations such as repeaters, RIS, and ad hoc networks allows not only coverage extension but also the enhancement of communications performance.
- SUPERIOT Application 3.6 - Resource extraction supported by IoT communication
    - Another relevant set of applications includes cases related to resource extraction. Two cases are considered, namely non-renewable resources as well as renewable resources. The former includes underground mining, open-pit mining, oil drilling, etc., whereas the latter consider forestry/logging and water systems, for instance. Different connectivity strategies can be used for these applications, depending on the requirements of the service. Some environments could be quite demanding from the standpoint of connectivity, for instance, underground mining. Radio waves do not propagate well underground and optical channels are also affected by scattering and other phenomena due to the fine dust suspended in the air. The SUPERIOT concept offers in principle a dual-mode communication approach that can provide a robust connectivity approach. Parallel optical-radio transmission, angular diversity, repeaters, and ad hoc networking can be used to improve performance or extend coverage in demanding environments such as underground mining.
- SUPERIOT Application 3.7 - Intelligent transportation systems
    - The dual-mode communication (light and radio) can be used to increase vehicle-to-vehicle (V2V) and vehicle-to-everything (V2X) reliability of communications, improving critical-communications situations, such as safety communications. The possibility of using printed electronics for the SUPERIOT nodes allows for sticker-like appliances that can be used on car windows, creating intelligent transportation

systems (ITS). Reconfigurable intelligent surfaces with large energy harvesting surfaces can be attached to buildings, increasing traffic safety at road intersections, minimizing congestion, and avoiding accidents. Sticker-like wearable nodes can also be used to create vehicle-to-driver/passenger as well as vehicle-to-pedestrian communications to automate processes and generate alerts that could help prevent accidents.

- SUPERIOT Application 3.8 - Sensorization and IoT communication in remote zones
  - SUPERIOT technology could allow for sensorization in remote zones, where energy supply is challenging, but there are temporary light sources, such as passings cars. These autonomous sensors (e.g., road sensors or others) could use light energy harvesting from passing cars to gather and communicate sensor data. Sensors not only harvest but also store energy. Taking into account that the amount of energy gathered from car lights would be low, it could be interesting to gradually accumulate energy from many cars before communicating. Sensors could exploit large-area photovoltaic cells to increase the amount of energy scavenged from a passing car.

3.4.3 Illustrative examples

The following images illustrate some of the possible applications of SUPERIOT enhanced IoT communication in demanding environments.

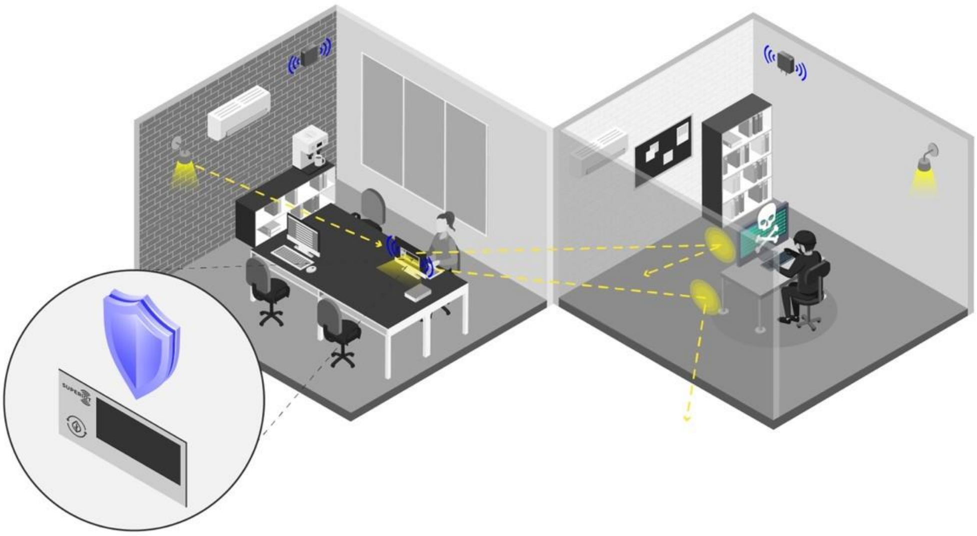


Figure 10. Scenario 3: enhanced security and privacy in IoT communications.

Figure 10 illustrates a situation where SUPERIOT technology can be used to enhance the privacy and security of communications. Radio communication is typically more vulnerable to eavesdropping or planned attacks as radio waves typically propagate through walls. As described in application 3.1, communications strategies based on the dual-mode connectivity can reduce this risk. In this figure, an attacker is not able to access the information from the other room.

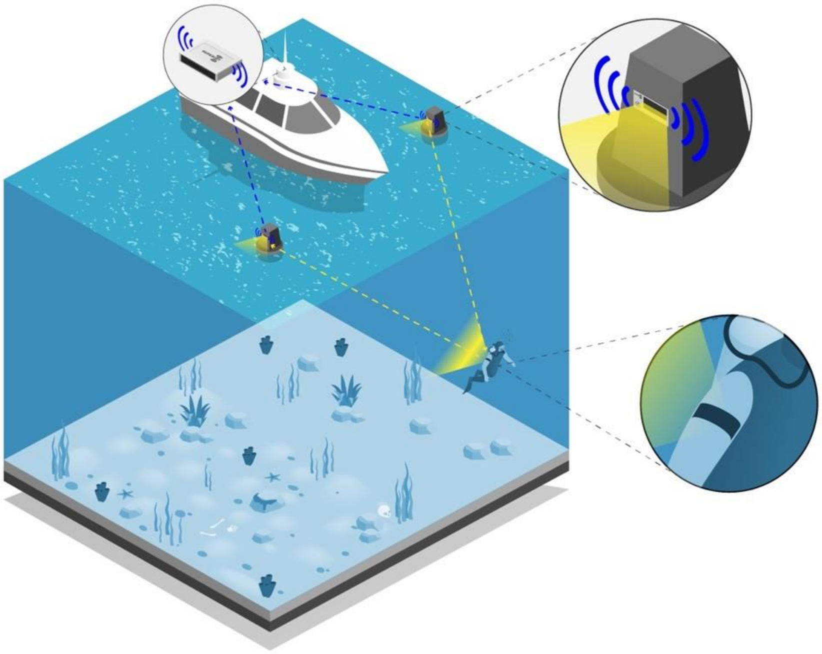


Figure 11. Scenario 3: enhancements in underwater IoT communications.

Figure 11 shows an underwater situation where radio communication is challenging (SUPERIOT Application 3.3). IoT nodes right on the surface provide connectivity through light below the surface (diver), and radio above the surface (boat). Printed electronics would help create nodes that are autonomous, environmentally friendly, and can be easily adapted to a liquid environment.

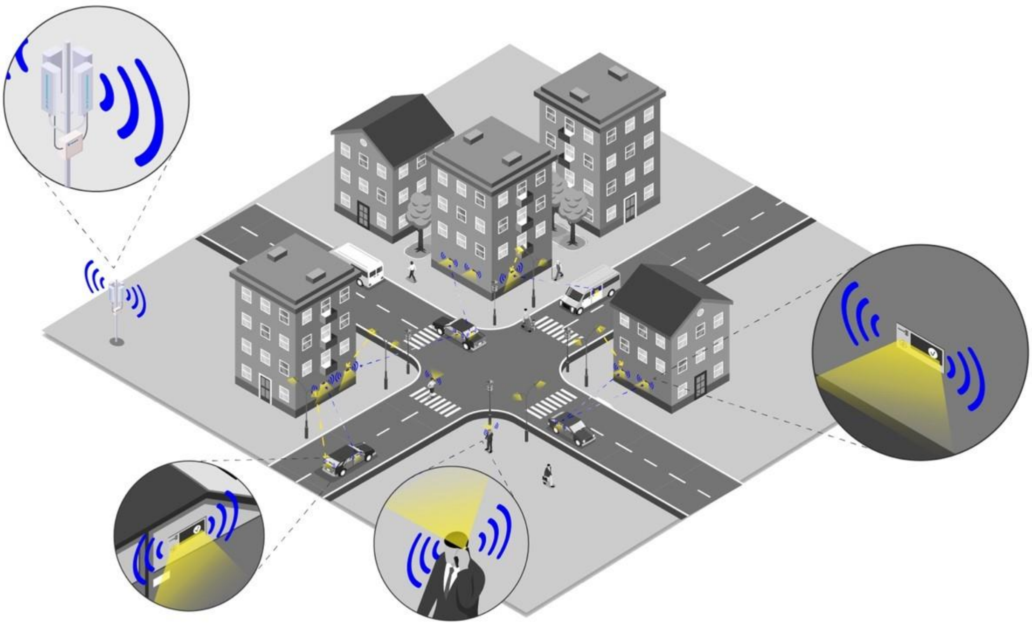


Figure 12. Scenario 3: coverage extension with large-area IoT nodes.

Finally, nodes or related supporting devices used to provide coverage extension are shown in Figure 12. As described in application 3.5, printed electronics could be used to create autonomous sticker-like network nodes and repeaters or reconfigurable intelligent surfaces. This would help improve the quality of IoT communications in situations where there is not enough network coverage. The dual-mode connectivity is depicted in the figure to illustrate the adaptability to dynamic communication situations.

4 User requirements

This section presents user requirements for the different scenarios and corresponding applications.

As described in the previous section, the first two scenarios (smart tags and labels, and large-scale sensing and actuation) include applications closer to the end user. For this reason, the user requirements of the first two scenarios are based on the probable performance expectations of an end user. The main benefit of this approach is that we start by defining what a smart tag and label (SUPERIOT-SCN-1) and large-scale sensors and actuators (SUPERIOT-SCN-2) are expected to do from a user perspective. At this point in the project, this helps align the partners towards a common vision for the development of SUPERIOT technology.

The third scenario (enhanced IoT communication in demanding environments) focuses on technological approaches that may be used by different user applications. Hence, in this scenario, the user requirements are more focused on a possible technology taker that can apply SUPERIOT for different products or purposes.

4.1 Methodology for defining user requirements

The methodology for defining user requirements was based on mind maps (Appendix 2). A mind map consists of a diagram used to organize information into a hierarchy, showing relationships among pieces driven from the central concept.

The mind map process used for identifying the requirements followed a two-step approach. First, a brainstorming session was made to generate requirements. In this step, the different participants identified possible requirements without fully evaluating the relevance or the feasibility of such requirements. The goal is to generate different ideas to fill the mind map. The second step consisted of creating groups with people from different fields and having different technical background. These groups reviewed the suggested requirement ideas and discussed the relevance for the central concept and feasibility of each requirement.

After having the requirements for the scenarios, we performed a more detailed discussion of the importance of each requirement per application, together with a qualitative analysis of the feasibility of such requirement in the project framework. This analysis was based on the current technology perception of the partners and needs to be revised and refined throughout the project.

For each application, a table is presented with the results. In these tables, both the importance of the requirement and the expected feasibility consider the specific characteristics of the application. The expected timeline of technology matureness needed to develop the first prototypes is also estimated, in order to better understand what types of applications are more realistic in the timeline of the project.

The obtained results were used to help in the prioritization and selection of the most promising applications for each demonstrator.

4.2 SUPERIOT-SCN-1: smart tags and labels

4.2.1 Scenario requirements

This scenario presents a vision of the smart tag/label of the future. Based on the general vision described before, a mind map was created to generate ideas for user requirements. The selection of the user requirements and their priority considers their relevance to the vision, but also the predictable feasibility of such requirement in the SUPERIOT project.

The possible user requirements were divided into the following main groups:

- Wireless connectivity

- Sensors
- Actuators
- Positioning RF and/or Light
- Energy autonomy
- Cost efficient to manufacture
- Reusable/repurposable
- Eco-friendly
- Disposability

Inside each of these main groups, different structures were used to collect the user requirements.

Wireless connectivity

Wireless connectivity is a key requirement that a smart tag/label needs to have to operate attached to moving objects, products, and people. The wireless connectivity requirements were divided in the following subgroups:

- RF communications
- Light communications
- Remotely configurable
- Uni/bidirectional communication
- Energy efficient communications
- Reliable communications
- Secure/private communications
- Safe communications

Regarding RF communications, there is a common ground understanding that these smart tags and labels need to have at least short-range RF connectivity, so they can operate connected to personal area networks or local networks. Mesh networks, wide area networks, or even satellite communications would create more possibilities of applications, enabling monitoring and actuation in situations where local networks are not available. This is important for example in outdoor scenarios, or in situations where the products and/or people need to be in constant communication over larger distances (e.g., supply chain). However, this challenge is considered to be outside of the scope of the project.

Light communications are also a fundamental point of the project. Short range point to point is the minimum essential communication level for demonstrating the potential of SUPERIOT. Fixed directional beams are considered as an important feature to implement point-to-point communication, especially for the reason that they compliment often omni-directional radio connectivity. Visible light communication is still an emerging technology, and VLC standards are still in progress. Due to this, it is still difficult to predict the viability of applying local networks and personal area networks of light communication in the project, making them a nice-to-have and not a focus of SUPERIOT. Dynamic or adaptive beam-forming techniques are also considered to be out of the scope of SUPERIOT prototypes.

The proposed dual-mode light and radio communication is especially relevant for the future if there is the possibility of dynamically selecting between them, making this requirement an important part of SUPERIOT. Regarding unidirectional vs bidirectional communication, both possibilities are important for a smart tag/label. Unidirectional communication may be relevant in environments where there is a need to spare energy, while bidirectional communication is crucial for the development of a truly “smart” product, with monitoring and actuation capabilities.

Other general communication requirements were discussed: energy efficiency, reliability, security/privacy and safety. Energy efficiency is one of the main goals of SUPERIOT and scavenging of energy from communications or dedicated energy transmissions is one of the topics that must be explored during the project. A more complex, but still an interesting requirement for the project, is the possibility of waking up the system over light and RF. Reliability in communication and safety for operation near humans are also mandatory, even in prototype stages. Topics related to security/privacy and possible interference with other systems are considered to be relevant, but not a major concern for the project and its demonstrators.

Sensors

Even though the main purpose of smart tags and labels are the identification and tracking of objects and people, a group of interesting applications emerges if sensors are added to the smart tag/label. Product quality assessments and cold-chain monitoring are some of the applications that benefit from the possibility of monitoring the condition of the products/people. For this purpose, the selection of the main sensors for this scenario is based on the type of applications the tags and labels are mostly used, leaving environment monitoring for other scenarios.

Temperature and humidity measurements are commonly tied to the quality assessment of products, so the corresponding sensors are important for the smart tag and label proposed in the project. The same applies to sensors that can be used to detect impacts or other movements that may damage goods. The accelerometer and magnetometer, in particular, could also be used for monitoring activity, helping adjust parameters of communication of the smart tag/label. RF and light detectors are also important for this purpose and to help select the best communication alternative, enabling smart operation.

Actuators

The concept of a smart tag/label goes beyond sensing capabilities. The possibility of actuating in the tag/label or even in systems that are close to the tag/label are differentiating points, when compared to the existing tags and labels.

One of the fundamental parts of a smart label is its capability of supplying human-readable information that helps decisions that need to be made by people on site. For this purpose, the possibility of displaying light signals or simple icons indicating actions or alerts needs to be explored during the project. The same applies to segmented displays that can indicate the amount, date and times, or other important information for the users that are being tracked or for the goods that are being handled. A matrix display would be an important feature in the future, but not mandatory to demonstrate the proposed value of SUPERIOT.

Other actuators, such as vibration and buzzer may be important for safety applications in the future, namely, to alert a person carrying a smart tag in danger situations. If possible, the buzzer actuator may be explored in SUPERIOT. However, this is considered to be difficult to address during the timeline of the project.

Positioning RF and/or light

When identifying products and people, the location assessment is extremely important for decision making. Localization techniques are a key concept of SUPERIOT, and the initial idea is to take advantage of both radio and light communications for this purpose.

Positioning by network is probably the simplest option when it comes to tag/label positioning, since the network nodes are generally less restricted in terms of complexity and energy consumption. This is an option that must be considered in SUPERIOT.

Another key point to be explored in SUPERIOT is the possibility of using RF, light or a combination of to enhance localization capabilities. The concepts of network-initiated positioning and selectable position update frequency are more tied to the concept of "smart" tag/label. The first is tied to the bi-directional communication requirement, while the second implies that the tag is somehow aware of the dynamic context where it is being used. Both of these requirements are important for the project.

Energy autonomy

Nowadays, the concept of smart tag or label is normally tied with the need of battery supply. SUPERIOT explores the possibility of having autonomous nodes without the usage of conventional batteries. This enables the concept of smart tag or label without battery and fully autonomous.

One important aspect for having a truly autonomous tag/label is the possibility of storing energy. Some of the applications that are going to be demonstrated in the project may only be possible with the help of conventional batteries. This means that during the timeline of SUPERIOT development, battery operation requirements may still need to be considered. Nonetheless, the project is going to focus on the no-battery goal and using alternatives to conventional batteries, such as (super) capacitors.

Since no-battery is a future goal of SUPERIOT, energy scavenging is practically mandatory. The project will focus on the requirements related to light and radio energy harvesting, taking advantage of the interfaces already proposed. Mechanical and heat energy harvesting may be considered for other purposes, but they are not an evident benefit for the smart tags and labels. Wind, water, friction, and movement may not occur in many environments where the tags and labels attached to products and people are going to operate.

More advanced requirements connected with having an energy aware system are left out of the scope of the project. Energy predictions that help the tag/label make decisions regarding its operations or even energy "swarm" of multiple tags/labels are too complex and not as relevant for the project as the requirements described before.

Cost-efficient manufacturing

For the "truly sustainable" SUPERIOT nodes, cost efficiency is an important topic. There are many possible requirements related to cost-efficient manufacturing, namely: material costs, manufacturing costs, energy consumption, among others. In the scope of the project, the main requirement for the smart tags and labels is to reduce the cost of technology by using abundant elements or materials, rather than endangered or critical ones, or coming from conflict zones. To be able to greatly produce smart tags and labels in the future, the cost of the materials is critical, and pursuing a future fully printed node is one of the goals of the project.

If possible, there is going to be also a special concern for the requirement of reducing manufacturing costs and trying to aim for a modular manufacturing platform.

Reusable/repurposable

Having a reusable and repurposable tag/label is one of the main differences from the existing solutions. This requirement is very important for the relevance of SUPERIOT technology. The idea of a "future proof" solution is directly tied to the concept of reusable and repurposable, and there is no "future proof" solution without standardization. In this sense, standardization is a major requirement for SUPERIOT technology.

Other requirements that help reusability and adaptability to different purposes is the possibility of having a tag/label that is modular, upgradable, and repairable. These requirements should be considered in the future, but they are not going to be considered during the project.

Eco-friendly

SUPERIOT technology aims to be truly sustainable in a holistic way, considering the complete lifecycle of the products. This is an important general requirement for SUPERIOT technology, and the more specific requirements of low carbon footprint, no ecotoxicity, and cradle-to-cradle approach, will be a focus during the project.

Disposability

Disposability is a sensible topic for the project. The main purpose of SUPERIOT is to create reusable and repurposable technology. In this sense, disposability is not a focus, however, there are certainly applications for smart tags and labels where reusability will not be an option. Taking this into account, the smart tags and labels must not be harmful for the environment, at the very worst scenario, they should be able to be disposed as "normal waste". Nevertheless, it is important to explore during the project the possibility of making them recyclable or even biodegradable in the future.

4.2.2 Application requirements

Table 1. Requirements for smart labels attached or incorporated in day-to-day market products and its feasibility as part of the project demonstrators.

Application	Requirements (mind map) *examples*	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
1.1 - Smart labels attached or incorporated in day-to-day market products	**Dual-mode connectivity** *- RF communication (short range)* *- Light comms (short range point to point; supporting IoT applications)*	**H**	**M-H**	**ST-LT**	**Demo 1** **Demo 3** (with lower functionality)
	Sensors - Temperature	**M**	**H**		
	Actuators - Readable information (visual indicator or segmented display)	**M**	**H** (Possibly via external contract)		
	Dual-mode positioning (RF and light)	**M**	**M-H**		
	Privacy/security	**H**	**M-H**		
	Disposable - Recyclable	**H**	**M**		
	Reusable	**L-M**	**H**		
	Eco-friendly	**H**	**M**		
	Cost-efficient to manufacture - Material Cost	**H**	**M**		
	Energy autonomy - Energy storage (no battery) - Scavenging (RF and light)	**H**	**M**		

Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).

Table 2. Requirements for smart tags incorporated in sensitive items and its feasibility as part of the project demonstrators.

Application	Requirements (mind map) *examples*	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
1.2 - Smart tags incorporated in sensitive items (high-value, high-risk, among others)	**Dual-mode connectivity** *- RF communication (short range)* *- Reliable communication* *- Bi-directional*	**H**	**M-H**	**NI-ST**	**Demo 1** **Demo 3** (with lower functionality)
	Sensors: *- RF detector* *- Radiation*	**L-M**	**M**		
	Actuators	**L**	**H** (Possibly via external contract)		
	Dual-mode positioning *- Positioning by network*	**L-M**	**M-H**		
	Security/privacy	**H**	**M-H**		
	Disposable	**L**	**M**		
	Reusable *- Standardization/ universal*	**M**	**M**		
	Eco-friendly	**M**	**M**		
	Cost efficient to manufacture: *- Material Cost* *- Energy efficient*	**L**	**M**		
	Energy autonomy: *- Energy storage (no battery)* *- Scavenging (Radio)*	**H**	**M**		

Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).

Table 3. Requirements for tags and labels specifically designed for food and medicines and its feasibility as part of the project demonstrators.

Application	Requirements (mind map) *examples*	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
1.3 - Tags and labels specifically designed for medicines	**Dual-mode connectivity** *- RF communication (short range; local networks)* *- Light comms (short range point to point; supporting IoT applications)* *- Reliable communication* *- Bi-directional*	**H**	**M-H**	**ST**	**Demo 2**
	Sensors *- RF detector*	**L-M**	**M**		
	Actuators	**L**	**H** (Possibly via external contract)		
	Dual-mode positioning *- Positioning by network*	**H**	**M-H**		
	Security/privacy	**H**	**M-H**		
	Disposable	**M**	**L-M**		
	Reusable	**L**	**M**		
	Eco-friendly	**H**	**M**		
	Cost efficient to manufacture *- Material Cost* *- Energy efficient*	**H**	**M**		
	Energy autonomy *- Energy storage (no battery)* *- Scavenging (Radio)*	**H**	**M**		

Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).

Table 4. Requirements for labels specifically designed for logistic operations and its feasibility as part of the project demonstrators.

Application	Requirements (mind map) *examples*	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
1.4 - Labels specifically designed for logistic operations	**Dual-mode connectivity** *- RF communication (short range; local networks)* *- Light comms (short range point to point; supporting IoT applications)* *- Reliable communication* *- Bi-directional*	**H**	**M-H**	**NI-ST**	**Demo 1** **Demo 2**
	Sensors *- RF detector*	**L-M**	**M**		
	Actuators	**L**	**H** (Possibly via external contract)		
	Dual-mode positioning *- Positioning by network*	**H**	**M-H**		
	Security/privacy	**H**	**M-H**		
	Disposable	**M**	**L-M**		
	Reusable	**L-M**	**M**		
	Eco-friendly	**H**	**M**		
	Cost efficient to manufacture *- Material Cost* *- Energy efficient*	**H**	**M**		
	Energy autonomy *- Energy storage (no battery)* *- Scavenging (Radio)*	**H**	**M**		

Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).

Table 5. Requirements for enhanced label for batch manufacturing and its feasibility as part of the project demonstrators.

Application	Requirements (mind map) *examples*	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
1.5 - Enhanced labels for batch manufacturing	**Dual-mode connectivity** *- RF communication (short range; local networks)* *- Light comms (short range point to point; supporting IoT applications)* *- Reliable communication* *- Bi-directional*	**H**	**M-H**	**NI-ST**	**Demo 1** **Demo 2**
	Sensors *- RF detector*	**L-M**	**M**		
	Actuators	**L**	**H** (Possibly via external contract)		
	Dual-mode positioning *- Positioning by network*	**H**	**M-H**		
	Security/privacy	**H**	**M-H**		
	Disposable	**M**	**L-M**		
	Reusable	**L-M**	**M**		
	Eco-friendly	**H**	**M**		
	Cost efficient to manufacture *- Material Cost* *- Energy efficient*	**H**	**M**		
	Energy autonomy *- Energy storage (no battery)* *- Scavenging (Radio)*	**H**	**M**		

Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).

Table 6. Requirements for tags incorporated in shelves or in other small product packages and its feasibility as part of the project demonstrators.

Application	Requirements (mind map) *examples*	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
1.6 - Tags incorporated in shelves or in other small product packages	**Dual-mode connectivity** *- RF communication (short range; local networks; supporting IoT applications)* *- Light comms (short range point to point; supporting IoT applications)* *- Reliable communication* *- bi-directional*	**M**	**M-H**	**NI-ST**	**Demo 1**
	Sensors *- RF detector* *- Light conditions* *- Processed data* *- Pressure*	**L**	**M**		
	Actuators *- Light indicator* *- Tactile* *- Readable information (segmented display)*	**H**	**M**		
	Dual-mode positioning *- Positioning by network*	**L**	**M-H**		
	Security/privacy	**M**	**M-H**		
	Disposable	**L**	**L-M**		
	Reusable *- Standardization/ universal*	**M**	**L-M**		
	Eco-friendly	**M**	**M**		
	Cost efficient to manufacture *- Material Cost* *- Energy efficient*	**M**	**M**		
	Energy autonomy *- Energy storage (battery)* *- Scavenging (Radio)*	**H**	**M**		

Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).

Table 7. Requirements for tags and labels for healthcare patients and its feasibility as part of the project demonstrators.

Application	Requirements (mind map) *examples*	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
1.7 - Tags and labels for healthcare patients	**Dual-mode connectivity** *- RF communication (short range; local networks; supporting IoT applications)* *- Light comms (short range point to point; supporting IoT applications)* *- Reliable communication* *- bi-directional*	**H**	**M-H**	NI-ST	**Demo 1** **Demo 2**
	Sensors *- RF detector* *- Processed data*	**M**	**M**		
	Actuators *- Light indicator* *- Readable information (segmented display)*	**L**	**M-H**		
	Dual-mode positioning *- Positioning by network*	**H**	**M-H**		
	Security/privacy	**H**	**M-H**		
	Disposable	**H**	**L-M**		
	Reusable: *- Standardization/ universal*	**M**	**L-M**		
	Eco-friendly	**M**	**M**		
	Cost efficient to manufacture *- Material Cost* *- Energy efficient*	**M**	**M**		
	Energy autonomy *- Energy storage (no battery)* *- Scavenging (Radio)*	**H**	**M**		

Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).

Table 8. Requirements for tags for smart pills and its feasibility as part of the project demonstrators.

Application	Requirements (mind map) *examples*	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
1.8 - Tags for smart pills	**Dual-mode connectivity** *- RF communication (short range; local networks; supporting IoT applications)* *- Reliable communication* *- bi-directional*	**H**	**L**	**LT**	**Demonstration outside the scope of the project**
	Sensors *- RF detector* *- Processed data*	**M**	**L**		
	Actuators	**L**	**L**		
	Dual-mode positioning *- Positioning by network*	**L**	**L**		
	Privacy/security	**L**	**L**		
	Disposable	**H**	**L**		
	Reusable *- Standardization/ universal*	**L**	**L**		
	Eco-friendly	**H**	**L**		
	Cost efficient to manufacture *- Material Cost* *- Energy efficient*	**H**	**L**		
	Energy autonomy *- Energy storage (no battery)*	**H**	**L**		

Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).

Table 9. Requirements for labels for tracking critical equipment and its feasibility as part of the project demonstrators.

Application	Requirements (mind map) *examples*	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
1.9 - Labels for tracking critical equipment	**Dual-mode connectivity** *- RF communication (short range; local networks; supporting IoT applications)* *- Light comms (short range point to point; supporting IoT applications)* *- Reliable communication* *- bi-directional*	**H**	**M-H**	**NI-ST**	**Demo 1** **Demo 2**
	Sensors: *- RF detector* *- Processed data* *- Temperature* *- Accelerator* *- Radiation*	**M**	**L-M**		
	Actuators *- Light indicator* *- Readable information (segmented display)*	**M**	**M-H**		
	Dual-mode positioning *- Positioning by network*	**H**	**M-H**		
	Security/privacy	**H**	**M-H**		
	Disposable	**L**	**L-M**		
	Reusable *- Standardization/ universal*	**M**	**L-M**		
	Eco-friendly	**L**	**M**		
	Cost efficient to manufacture *- Material Cost* *- Energy efficient*	**L**	**M**		
	Energy autonomy *- Energy storage (battery)* *- Scavenging (Radio)*	**H**	**M**		

Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).

Table 10. Requirements for tags for animal monitoring and management and its feasibility as part of the project demonstrators.

Application	Requirements (mind map) *examples*	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
1.10 - Tags for animal monitoring and management (livestock and wildlife)	**Dual-mode connectivity** *- Light comms (short range point to point; supporting IoT applications)* *- Reliable communication* *- bi-directional*	**H**	**M-H**	**ST-LT**	**Demo 1**
	Sensors *- Light conditions* *- Processed data* *- Temperature*	**L**	**M**		
	Actuators	**L-M**	**M**		
	Dual-mode positioning *- Positioning by light*	**H**	**M-H**		
	Security/privacy	**L**	**M**		
	Disposable	**M**	**L-M**		
	Reusable	**M-H**	**L-M**		
	Eco-friendly	**H**	**M**		
	Cost efficient to manufacture *- Material Cost* *- Energy efficient*	**L**	**M**		
	Energy autonomy *- Energy storage (no battery)* *- Scavenging (light)*	**H**	**M**		

Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).

Table 11. Requirements for tags to increase collectible cards gaming experience and its feasibility as part of the project demonstrators.

Application	Requirements (mind map) *examples*	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
1.11 - Tags to increase collectible cards gaming experience	**Dual-mode connectivity** *- RF communication (short range; local networks; supporting IoT applications)* *- Light comms (short range point to point; supporting IoT applications)* *- Reliable communication* *- bi-directional*	**H**	**M**	**LT**	**Demonstration outside the scope of the project**
	Sensors *- RF detector* *- Processed data* *- Light conditions* *- Temperature*	**L-M**	**M**		
	Actuators	**L**	**L-M**		
	Security/privacy	**L**	**M**		
	Dual-mode positioning *- Positioning by network*	**M**	**M**		
	Reusable - Standardization/ universal	**M**	**L-M**		
	Disposable	**M-H**	**L-M**		
	Eco-friendly	**H**	**L-M**		
	Cost efficient to manufacture - Material Cost - Energy efficient	**H**	**M**		
	Energy autonomy - Energy storage (no battery) - Scavenging (Radio)	**H**	**M**		

Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).

4.3 SUPERIOT-SCN-2: large-scale sensing and actuation

4.3.1 Scenario requirements

Similar to Scenario 1, a vision and a mind map of Scenario 2 dedicated to exploitation of sensing methodologies in a broad range of environments was performed. A selection of the user requirements and their priority considers their relevance to the vision, but also the feasibility of such requirement in the SUPERIOT project. This scenario relies on the ability to produce sensors in huge quantities allowing for the implementation in more industrial or large areas scenario.

The following characteristics are expected under these more massive applications:

Communications

Concerning communications, there are applications where uni-directional communication may be sufficient, but there will be situations where bi-directional communications for instance when actuation is needed or the node needs to confirm the integrity of the received data. Communication reliability, safety and efficiency are also relevant points to ensure the feasibility of the different applications. For large-scale deployment of sensors and actuators, RF long-range communication is essential. Short-range light communications may be interesting in situations where radio communications are difficult and there are controlled and connected light sources nearby.

Sensors

Within this scenario of large-scale sensing and actuation, we envision the possibility of efficiently producing huge quantities of printed sensors. This will enable applications for monitoring large agriculture fields, smart cities, construction buildings, transportation, and so on. For all these different applications, a broad range of printed sensors may be used to gather important data:

- Temperature and humidity
- Sensors for air/water quality monitoring and to detect environmental agents (pH, sugar levels, pollutes...)
- Light and acoustic sensors for light/sound conditions
- Mechanical stress sensors
- Motion sensors, accelerometers and magnetometers
- Rf detectors

The selection of the different possible sensors will be based on the final applications.

Actuation

The sensed parameters could be used to drive different actions depending on the application that is selected. Unlike Scenario 1 where displays were the main actuators, in this scenario a more active response is required. The required actuators may be used to lock/unlock volume containers, to start or stop specific processes or to activate additional sensors for better analysis of the environment’s new conditions.

Energy autonomy

Unlike scenario SCN-1 in this case there is more flexibility in the size or cost, therefore more complex strategies for energy storage and awareness are contemplated, including battery uses and more capable energy scavenging systems.

Cost-efficient manufacturing

As a general aim of the project, the reduction in material cost, manufacturing facilities, and energy consumption, among others, are relevant issues to address.

Reusability/repurposability capability

This characteristic allows the devices to be flexible and adaptable to different applications without significant modifications. Some of the main properties related to this are the possibility of having a reconfigurable/modular scheme, the implementation of standardized or universal sets/modules available for combining. These modules should be upgradable, enabling the reuse of previous devices and repairable for extending the elements working life. These aspects provide a vision for the future, taking into account possible new applications in system design.

Eco-friendly

The full system requires more energy and autonomy and therefore we cannot at this point foresee a fully eco-neutral implementation. Nevertheless, assuring a low ecotoxicity of the implementation materials and minimization of resource utilization throughput the operation are required.

4.3.2 Application requirements

Table 12. Requirements for sensors and actuators for smart buildings and its feasibility as part of the project demonstrators.

<table>
<tr><th>Application</th><th>Requirements
(mind map)
examples</th><th>Importance of the requirement (I/L/M/H)</th><th>Expected feasibility within the project framework (I/L/M/H)</th><th>Expected timeline for technology matureness</th><th>Possible demonstrator(s)</th></tr>
<tr><td rowspan="7">2.1 - Sensors and actuators for smart buildings</td><td>Dual-mode communication</td><td>H</td><td>M-H</td><td rowspan="7">NI-ST</td><td rowspan="7">Demo 1
Demo 3 (with lower functionality)</td></tr>
<tr><td>Sensors
- temperature
- humidity
- light
- RF</td><td>H</td><td>M</td></tr>
<tr><td>Actuators</td><td>H</td><td>M</td></tr>
<tr><td>Energy autonomy</td><td>M-H</td><td>M</td></tr>
<tr><td>Cost-efficient manufacturing</td><td>H</td><td>M</td></tr>
<tr><td>Reusable</td><td>M-H</td><td>L-M</td></tr>
<tr><td>Eco-friendly</td><td>H</td><td>M</td></tr>
<tr><td colspan="6">Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).</td></tr>
</table>

Table 13. Requirements for sensors and actuators for construction monitoring and its feasibility as part of the project demonstrators.

Application	Requirements (mind map) *examples*	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
2.2 - sensors and actuators for construction monitoring	**Dual-mode communication**	**H**	**M-H**	**NI-ST**	**Demo 1** **Demo 4**
	Sensors *- temperature* *- strain* *- acoustic*	**H**	**M**		
	Actuators *- sound alarm* *- transmitted alarm*	**H**	**M**		
	Energy autonomy	**M-H**	**M**		
	Cost-efficient manufacturing	**H**	**M**		
	Reusable	**M-H**	**L-M**		
	Eco-friendly	**H**	**M**		

Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).

Table 14. Requirements for sensors for medical and safety applications and its feasibility as part of the project demonstrators.

Application	Requirements (mind map) *examples*	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
2.3 - sensors for medical and safety applications	**Dual-mode communication**	**H**	**M-H**	**NI-ST**	**Demo 1** **Demo 2**
	Sensors - humidity - pH - O2 - chemical sensing (gas) - RF - radiation	**H**	**M**		
	Actuators	**H**	**M**		
	Energy autonomy	**M-H**	**M**		
	Cost-efficient manufacturing	**M**	**M**		
	Reusable	**H**	**L-M**		
	Eco-friendly	**M**	**M**		

Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).

Table 15. Requirements for sensors and actuators applied to smart cities and its feasibility as part of the project demonstrators.

Application	Requirements (mind map) *examples*	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
2.4 - sensors and actuators applied to smart cities	**Dual-mode communication**	**H**	**M-H**	**NI-ST**	**Demo 1** **Demo 4**
	Sensors - CO2, ozone - Ultraviolet (UV) - magnetic field - acceleration - acoustic - RF	**H**	**M-H**		
	Actuators	**H**	**M-H**		
	Energy autonomy	**H**	**M**		
	Cost-efficient manufacturing	**H**	**M**		
	Reusable	**H**	**L-M**		
	Eco-friendly	**H**	**M**		
Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).					

Table 16. Requirements for sensors and actuators applied to smart agriculture and forestry and its feasibility as part of the project demonstrators.

Application	Requirements (mind map) *examples*	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
2.5 - sensors and actuators applied to smart agriculture and forestry	**Dual-mode communication**	**H**	**M-H**	**LT**	**Demonstration outside the scope of the project**
	Sensors - temperature, humidity - pH - UV - pollen - ozone - pollutants	**M**	**M**		
	Actuators - lock/unlock containers - open/close valves	**H**	**M**		
	Energy autonomy	**H**	**M**		
	Cost-efficient manufacturing	**H**	**M**		
	Reusable	**M-H**	**L-M**		
	Eco-friendly	**H**	**M**		
Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).					

4.4 SUPERIOT-SCN-3: enhanced IoT communication in demanding environments

4.4.1 Scenario requirements

This scenario considers IoT communication in a number of demanding environments. Even though IoT communication is the main focus of the scenarios, other IoT-related activities could be involved. The general vision of the scenario was first developed from which the requirements were produced following a mind map approach. In this scenario, demanding environments refer to either demanding IoT communication requirements, as in the case of applications 3.1 and 3.2, or demanding operating environments, as in the case of applications 3.3 - 3.8. The first two applications (3.1 and 3.2) are related to the characteristics of IoT connectivity, namely security and privacy, as well as reliability of communications, whereas the remaining applications are associated with environments that are challenging, such as underwater, vehicular, remote places, etc.

The following characteristics of the SUPERIOT concept are expected to be relevant in the applications in demanding scenarios.

Dual-mode connectivity

This is a central capability and asset of the concept, that can be greatly exploited to enhance communication performance despite the challenges imposed by the operating environment, such as mobility, difficult signal propagation, remoteness, and others. The type of available communication infrastructure is also related to the application. In some cases, the infrastructure supporting radio and light communications is present all the time, such as indoor environments, where local access is easy to provide. In other cases, such as remote locations and some outdoor environments, the continuous availability of networks providing connectivity cannot be guaranteed. Wide area (cellular) networks can typically provide radio connectivity to IoT devices over large areas. Also, opportunistic or on-demand connectivity can provide access to wireless networks. In these cases, for example, unmanned aerial vehicles (UAVs) or high-altitude platform stations (HAPS) with radio and/or optical transceivers onboard can be used to provide occasional connectivity.

Energy autonomy for the node

Dual energy harvesting (RF- and light-based) brings robustness and reliability to the operation of the IoT nodes and therefore to the network as well. The size of the IoT node has a big impact on energy harvesting capabilities. Small form factor limits the amount of optical energy that can be scavenged. In some cases, however, such as in remote locations and coverage extension approaches, designing large form factor IoT nodes is desirable to increase the energy harvesting capability. Energy autonomy could be critical in some applications where IoT sensors are difficult to reach, such as in-body applications, for instance.

Dual-mode positioning

Positioning in general is a requirement that is highly related to the type of application. In some cases, it may be irrelevant, such as in remote places, and in-body applications, though, in other applications of this scenario, positioning, and particularly the dual mode approach could bring unique advantages. An example could be an application where secure communication is required (application 3.1). The knowledge of the whereabouts of the IoT device may be exploited to assess the security strategy used in communications. Upon detection of operation in a sensitive location, optical communications could be preferred, for instance.

Reconfigurability

Reconfigurability is another key capability of the concept and allows the system to adapt to changing situations and to changing requirements. Reconfiguration takes place at both node and network, and it mainly refers to deciding how the IoT communication will be carried out. For example, from the node perspective, it could be configured to use optical links, or radio links or both simultaneously for the communications, or it could decide what information could be transmitted over radio and what over optical channels. The reasons for using different configurations depend on the type of application.

Sustainable node implementation

Having a sustainable implementation of the IoT node is always relevant, but the requirement becomes increasingly important as the expected node volume grows. Some niche applications may require only a relatively small number of nodes, even when considered on a global scale, while other applications may require massive volumes of them. The environmental impact in the latter case is obvious.

Small form factor (Node)

This is also an application-dependent requirement, though the prevailing assumption for IoT is that nodes should be physically small. As discussed, small form factors impose limitations on the size of photovoltaic cells used to harvest energy, therefore limiting the amount of energy that the node can harvest over time, challenging the energy autonomy of the node. But in some applications, such as coverage extension (3.5) and sensorization of remote areas (3.8), nodes could be of large size. In-body application may require on the other hand very tiny form factors.

Low-cost

Cost is an important issue in general, and low-cost solutions should always be sought. Also, cost is related to the volumes needed. Creating solutions that are low-cost by design could support the rapid adoption and massive use.

For each of the identified applications a mind map was created. The mind map describes pertinent information related to the application, such as the most likely operating environments and the relevance of the main SUPERIOT capabilities to the application. Furthermore, given the demanding characteristics of the scenario, also some preliminary technical ideas related to possible communication strategies and basic functional requirements were outlined. These strategies and requirements will be thoroughly investigated in the project when specifying the systems to be used in the demonstrators. The developed mind maps corresponding to the applications of the SCN-3 scenarios are included in the Appendix 2.

4.4.2 Application requirements

Table 17. Requirements for secure and private IoT communication and its feasibility as part of the project demonstrators.

Application	Requirements (mind map)	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
3.1 - Secure and private IoT communication	**Dual-mode connectivity**	**H**	**H**	**NI**	**Demo 1** **Demo 2**
	Energy autonomy for the node	**M**	**M**		
	Dual-mode positioning	**H**	**M**		
	Reconfigurability	**H**	**H**		
	Sustainable node implementation	**M-H**	**M**		
	Small form factor (node)	**M-H**	**H**		
	Cost-efficient	**M-H**	**L**		

Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).

Table 18. Requirements for reliable IoT communication and its feasibility as part of the project demonstrators.

Application	Requirements (mind map)	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
3.2 - Reliable IoT communication	**Dual-mode connectivity**	**H**	**H**	**NI-ST**	**Demo 1** **Demo 2**
	Energy autonomy for the node	**M**	**H**		
	Dual-mode positioning	**M**	**H**		
	Reconfigurability	**M**	**H**		
	Sustainable node implementation	**M**	**M**		
	Small form factor (node)	**M-H**	**H**		
	Cost-efficient	**M-H**	**L**		
Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).					

Table 19. Requirements for underwater IoT communication and its feasibility as part of the project demonstrators.

Application	Requirements (mind map)	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
3.3 - Underwater IoT communication	**Dual-mode connectivity**	**M-H**	**L**	**NI-ST**	**Demonstration outside the scope of the project**
	Energy autonomy for the node	**H**	**L**		
	Dual-mode positioning	**L-H**	**L**		
	Reconfigurability	**M-H**	**L**		
	Sustainable node implementation	**M-H**	**L**		
	Small form factor (node)	**M-H**	**L**		
	Cost-efficient	**M**	**L**		
Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).					

Table 20. Requirements for in-body and on-body communication and its feasibility as part of the project demonstrators.

Application	Requirements (mind map)	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
3.4 - In-body and on-body communication	**Dual-mode connectivity**	**M-H**	**L**	**NI-ST**	**Demonstration outside the scope of the project**
	Energy autonomy for the node	**H**	**L**		
	Dual-mode positioning	**L-M**	**L**		
	Reconfigurability	**M-H**	**L**		
	Sustainable node implementation	**M-H**	**L**		
	Small form factor (node)	**H**	**L**		
	Cost-efficient	**M-H**	**L**		
Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).					

Table 21. Requirements for coverage extension with large-area IoT nodes and its feasibility as part of the project demonstrators.

Application	Requirements (mind map)	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
3.5 - Coverage extension with large-area IoT nodes	**Dual-mode connectivity**	**M-H**	**H**	**NI-ST**	**Demo 4**
	Energy autonomy for the node	**L-M**	**L**		
	Dual-mode positioning	**L-M**	**L**		
	Reconfigurability	**M-H**	**H**		
	Sustainable node implementation	**L-H**	**M**		
	Small form factor (node)	**L-M**	**L**		
	Cost-efficient	**M-H**	**M**		
Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).					

Table 22. Requirements for resource extraction supported by IoT communication and its feasibility as part of the project demonstrators.

Application	Requirements (mind map)	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
3.6 - Resource extraction supported by IoT communication	**Dual-mode connectivity**	**M-H**	**L**	**ST-LT**	**Demonstration outside the scope of the project**
	Energy autonomy for the node	**M-H**	**L**		
	Dual-mode positioning	**M**	**L**		
	Reconfigurability	**M**	**L**		
	Sustainable node implementation	**M-H**	**M**		
	Small form factor (node)	**L-H**	**L**		
	Cost-efficient	**L-H**	**L**		

Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).

Table 23. Requirements for intelligent transportation systems and its feasibility as part of the project demonstrators.

Application	Requirements (mind map)	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
3.7 - Intelligent transportation systems	**Dual-mode connectivity**	**H**	**L**	**ST-LT**	**Demonstration outside the scope of the project**
	Energy autonomy for the node	**L**	**L**		
	Dual-mode positioning	**M-H**	**L**		
	Reconfigurability	**H**	**L**		
	Sustainable node implementation	**M-H**	**L**		
	Small form factor (node)	**L-H**	**L**		
	Cost-efficient	**M-H**	**L**		

Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).

Table 24. Requirements for sensorization and IoT communication in remote zones and its feasibility as part of the project demonstrators.

Application	Requirements (mind map)	Importance of the requirement (I/L/M/H)	Expected feasibility within the project framework (I/L/M/H)	Expected timeline for technology matureness	Possible demonstrator(s)
3.8 - Sensorization and IoT communication in remote zones	**Dual-mode connectivity**	**L-H**	**L**	**ST-LT**	**Demonstration outside the scope of the project**
	Energy autonomy for the node	**H**	**L**		
	Dual-mode positioning	**L**	**L**		
	Reconfigurability	**M**	**L**		
	Sustainable node implementation	**L-H**	**L**		
	Small form factor (node)	**L-H**	**L**		
	Cost-efficient	**L-H**	**L**		

Note: I: irrelevant, L: Low, M: Medium, H: High; NI: Now and immediate future (0-3 years), ST: Short-term (within 10 years), LT: Long-term (beyond 10 years).

5 Applications and demonstrators

The goal of this section is to map the discussed applications to the different demonstrators proposed in the project. This process helps to define what types of applications should be further analyzed and considered during the project timeline. The result of this analysis is not a selection of what will be demonstrated. The main purpose is to understand which applications can be used to guide the development of the technology, and to help defining demonstrations that are relevant for end user applications.

In the previous section, user requirements for the different applications were derived, together with their expected feasibility within the project framework. The temporal scale was also included, indicating on the timeline when the technology is expected to be mature to realize the expected applications. Finally, the requirement table also identified the possible demonstrator where the application could be implemented.

Considering all these parameters, it is possible to identify the most promising applications for the project and distribute them among the different planned demonstrators. Figure 13 summarizes the process carried out in this initial study to identify and select the most promising applications per demonstrator. Central to this process are the capabilities of the SUPERIOT concept, as highlighted in Figure 1. The description of the four demonstrators at the project preparation phase was sketched based on these capabilities. The final selection of possible applications is competed below by choosing those applications that best match the description of the demonstrators while capitalizing on the key capabilities of the concept.

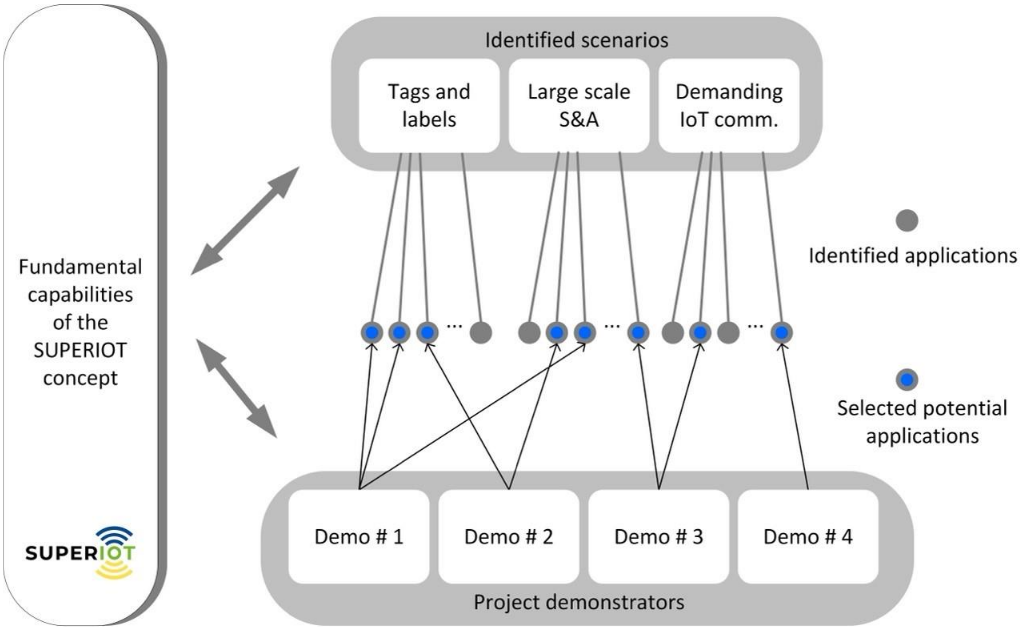


Figure 13. Outline of the application identification and selection process.

The four project demonstrators are 1) smart tag/label, 2) advanced logistics in medical ICT scenarios, c) fully printed IoT node and c) large-rea IoT node/repeater. An illustrative figure of these demonstrators is shown in Appendix 3.

Next, we present for each demonstrator a table with the selected potential applications.

Table 25. Selected potential applications per demonstrator.

Demonstrator	Potential Application
#1	1.2 - Smart tags incorporated in sensitive items
	1.4 - Tags specifically designed for logistic operations
	1.5 - Enhanced label for batch manufacturing
	1.6 - Tags incorporated in shelves or in other small product packages
	1.7 - Tags and labels for healthcare patients
	2.1 - Sensors and actuators for smart buildings
	2.2 - Sensors and actuators for construction monitoring
	2.3 - Sensors for medical and safety applications
	2.4 - Sensors and actuators applied to smart cities
	3.1 - Secure and private IoT communication
	3.2 - Reliable IoT communication
#2	1.3 - Tags and labels specifically designed for medicines
	1.4 - Tags specifically designed for logistic operations
	1.7 - Tags and labels for healthcare patients
	1.9 - Labels for tracking critical equipment
	2.3 - Sensors for medical and safety applications
	3.1 - Secure and private IoT communication
	3.2 - Reliable IoT communication
#3	1.1 - Smart labels attached or incorporated in day-to-day market products (with reduced capabilities)
	1.2 - Smart tags incorporated in sensitive items (with reduced capabilities)
	2.1 - Sensors and actuators for smart buildings (with reduced capabilities)
#4	2.2 - Sensors and actuators for construction monitoring
	2.4 - Sensors and actuators applied to smart cities
	3.5 - Coverage extension with large-area IoT nodes

6 Demonstrators and requirements

In this section, some examples of use cases are defined to derive possible ranges of values for each important parameter. The concept of a use case in this document is not the same as a scenario or application. The following definitions apply:

- Scenario: a vision of a SUPERIOT product or of a general technological concept that may be used to address different applications.
- Application: a possible current or future implementation of SUPERIOT technology to solve a specific challenge or to be applied in a certain environment where there is a benefit for the technology takers.
- Use case: a set of specific and sequential interactions between system and users in a particular environment and related to a particular goal.

As an example, a scenario can be the previously defined futuristic concept of a truly sustainable smart label. This scenario leads to many different possible applications in logistics, manufacturing, or healthcare. One example of application is the general usage of this futuristic smart label to better monitor the movements and conditions of goods during logistics. A use case is then a set of well-defined interactions that better exemplify what is expected in this application or in part of it. In this case, an initial step of a use case could be that the smart label is attached by a user to a product that is being monitored and associates the information of the product to that specific label.

In the description of use cases, a user story is created and used to define the set of interactions and the expected results of these interactions. In this sense, it is possible to define more specific constraints and map them to functional requirements of SUPERIOT.

6.1 Methodology for defining demonstrator requirements

The definition of requirements in this document aims to help guide the development of SUPERIOT technology to have relevance in real market applications in the future.

In this document, three promising scenarios were identified, and several different potential applications were described for these different scenarios. The different applications were then analyzed and mapped to the relevant proposed demonstrators.

As the demonstrators have different scopes and approaches, the way functional requirements were derived are not the same for all of them. Demonstrators 1 and 2 will most probably use the same hybrid printed electronics (PE) and silicon-based (Si-based) reference node. The versatility of this reference node makes it possible to demonstrate use cases that are closer to market applications. With that in mind, we analyzed some of the most common existing solutions for the different applications. This is relevant to understand how the key capabilities of SUPERIOT can be leveraged to bring innovation and added value to the market. To help define requirements, not only for this document, but also for future demonstrations, the environments where these applications are normally used were identified and the most relevant characteristics of these environments were then mapped. Finally, requirements were derived based on some examples of specific use cases. It would be impossible to cover use cases of all the potential applications, since different applications have very different requirements, some of them even contradictory. The use cases specified for demonstrators 1 and 2 are not meant to be necessarily the use cases to be demonstrated in the project, they are just examples to help define ranges of values for the requirements that can be seen as guidance for the development of SUPERIOT technology.

Demonstrator 3 followed a different approach as the main goal is to demonstrate the potential of PE technology in conjunction with IoT. Demonstrator 3 will not be a particular case of other demonstrators, but a stand-alone case developed to show in practice that the idea of a fully-printed IoT device is possible. This will hopefully serve as a concrete example demonstrating that truly sustainable IoT nodes can in fact be developed. In the section devoted to demonstrator

3, we make a more general analysis of what is expected to be feasible during the project. We also define some user requirements that will help reach a common understanding of what we are aiming for in the fully-printed node demonstration.

Demonstrator 4 focuses on a RIS (reconfigurable intelligent surface). The RIS is seen as a possible infrastructure add-on that may be used in many different applications. In that sense, the section of demonstrator 4 requirements is not focusing on the comparison of RIS to other solutions, but rather on how it is relevant in the project. In this section, we analyze how the different design parameters affect the performance of the RIS, based on simulations. This approach gives us a general idea on the necessary values for each parameter of the RIS, so that it is able to respond to different environments, helping to guide its development.

6.2 Preliminary studies

During the preliminary studies, different approaches for radio communication were explored.

One of the first discussions was the possibility of using either a standardized or proprietary protocol. The partners agreed on the general advantages of using a standardized protocol in order to shorten the to-market time and ease certification processes, making the solution easily scalable in the future, and increasing interoperability of the SUPERIOT solution by easing its integration with other existing nodes and networks.

For the selection of a standardized protocol, multiple different possibilities were considered, with the ones identified as the most promising being: passive RFID (e.g., NFC, UHF), Wi-Fi, WPAN (e.g., BLE, Zigbee, UWB), LPWAN (e.g., LoRaWAN, NB-IoT), and cellular.

In order to comply with the project's objectives and concept, several performance characteristics were analyzed to make a preferable choice.

Specifically, some of the key characteristics that want to be achieved in SUPERIOT are related to the potential massive application of the technology and dual-mode (light/radio) operation. This means that the future solution should be affordable, energy efficient with the potential of energy autonomous implementation, and capable of providing accurate positioning. Moreover, the need for light communication means that lighting infrastructure needs to be present in order to take advantage of dual-mode communication. For this reason, the most promising applications will probably be those operating in indoor environments. In that sense, communication range will not be as critical as the other points mentioned. However, data rates and latency are also important topics, since the project's concept also considers sensing and actuation for different purposes in the future.

Based on all these criteria, the final selection was to use Bluetooth Low Energy (BLE). BLE has a good balance of power efficiency, low chip cost and high availability, localization accuracy, data rates, and communication flexibility.

BLE consumes minimal power, allowing battery-operated devices to last months or years, which is a significant advantage over power-hungry alternatives like Wi-Fi and cellular networks. In essence, BLE is able to reduce energy consumption because the nodes are allowed to remain in sleeping mode most of the time. In addition, to overcome any potential communication range limitations, BLE offers a mesh networking paradigm. Compared to classic Bluetooth, the physical bandwidth is split into 40 orthogonal channels of 2 MHz each. The 40 physical channels are logically divided into two categories: 37 channels are used for regular data and 3 for advertising. This channel separation allows two data exchanging modes, namely, advertising mode and connection mode. Leveraging these two communication modes helps in achieving a fully autonomous node, where an appropriate mode is selected depending on reliability and energy constraints.

BLE chipsets are cost-effective, benefiting from widespread use in consumer electronics, whereas technologies like LoRaWAN and cellular tend to have higher costs. Due to its scalability and dense deployments, BLE also excels in localization accuracy, offering sub-meter precision, unlike the coarse localization of LoRaWAN or cellular. With data rates of up to 2 Mbps, BLE supports the needs of typical smart tags, far surpassing the low data rate of LoRaWAN and the excessive capacity of Wi-Fi and cellular. Finally, BLE provides configurable communication intervals, making it suitable for both frequent and low-power applications, in contrast to the continuous connectivity required by Wi-Fi or the infrequent transmissions of LoRaWAN.

Also, when this comes to sustainability, the high production volume, miniature size and low consumption make BLE chips more promising than the alternative solutions.

The following table shows some of the key aspects mentioned for the different technologies.

Table 26. Technical comparison table of different radio technologies.

	Backscatter	Short-range wireless & IoT		URLLC	UWB	BAN		Broad-band	mMTC & LPWAN			Satellite		
Technology	RFID	BLE	802.11 ax	DECT-2020	802.15.4z	802.15.6	SmartBAN	4G	NB-IoT	LoRaWAN	SIGFOX	NTN 5G	Inmarsat M2M	Iridium M2M
Deployment status	available	available	available	in devel-opment	available	in development		available	available			in devel-opment	available	
Standardi- za-tion body	multiple	Bluetooth SIG	IEEE	ETSI	IEEE	IEEE	ETSI	3GPP/ ETSI	3GPP/ ETSI	LoRa al-liance	proper	3GPP	proper	
Frequency band	multiple	2.4 GHz ISM	2.4 & 5 GHz ISM	1.9 GHz DECT	2.5-6 GHz ISM	0-10 GHz	2.4 GHz ISM	400 MHz-6 GHz licensed	700-2200 MHz licensed	sub GHz ISM		TBD	1600 MHz, L-band	
Average consumption when active[1,2]	passive	units mW	hundreds mW	not avail-able	dozens mW			hundreds mW	dozens mW			TBD	hundreds mW	
Range	meters	hundreds meters	dozens meters			meters		units kilome-ters	units-dozen kilometers			global		
Maximum throughput[1,3]	hundreds kbit/s	units Mbit/s	hundreds Mbit/s	units Gbit/s	hundreds Mbit/s	units Mbit/s		hundreds Mbit/s	dozens kbit/s	units kbit/s	dozens bit/s	TBD	dozens bytes per second	
Typical latency[1]	units ms	dozens ms	units ms	below one ms	units ms			dozens ms	hundreds ms -seconds		units sec-onds	TBD	dozens seconds	
Potential elderly-care use case	(i) track, (ii) sense	(i)IoT data, (ii)track, (iii)sense	(i)IoT data, (ii)track, (iii)sense, (iv)stream	(i)critical, (ii)stream	(i)IoT data, (ii)track, (iii)sense	(i)critical, (ii)IoT data, (iii)track, (iv)sense		(i)IoT data, (ii)track, (iii)stream	(i)IoT data, (ii)track			(i)IoT data, (ii)track, (iii)stream	(i)IoT data, (ii)track	

[1] Based on the data-sheets of state-of-the-art commercial chipsets and research literature.
[2] Peak consumption in a typical operation scenario.
[3] Peak physical-layer (PHY) throughput.

In summary, BLE was considered to be the most versatile and efficient radio interface for SUPERIOT's concept, offering the best combination of power efficiency, cost, location accuracy, and performance.

6.3 Demonstrator 1 – Sustainable Smart Tag

6.3.1 Demonstrator overview

Demonstrator 1 focuses on a full-capability small-form-factor reconfigurable optical-radio IoT node implemented with hybrid PE and Si-based technologies. This demonstrator includes the demonstration of a smart label/tag (dual-mode IoT node) and access point. Figure 14 depicts the general concept of demonstrator 1.

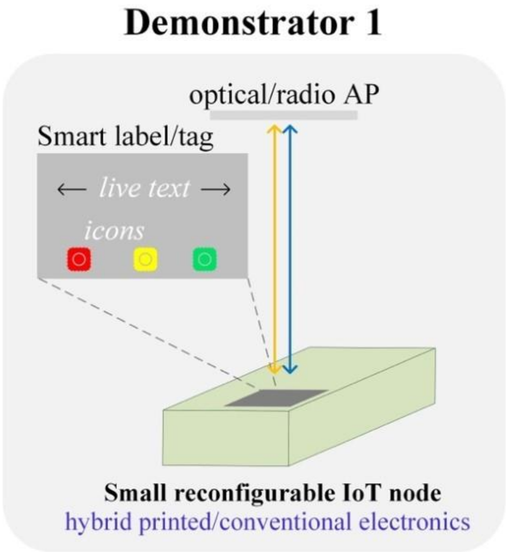


Figure 14. Demonstrator 1 concept.

Behind this demonstrator there is a future vision for a fully printed sticker-like autonomous reconfigurable IoT node with sensors, actuators, and connectivity functionalities. Attaching this label/tag to an object will transform the object into an IoT node. Massive production of these sustainable printed labels/tags will reduce their price to the cent level, creating a new world of opportunities for novel applications in packaging, wearables, logistics, medical ICT, entertainment, and industrial applications, among others. This vision will be attainable in the future, as printed electronics technology evolves. However, the smart tag/label can be implemented today with a hybrid technology, and that is the purpose of demonstrator 1.

The previous presented Table 25 shows the potential SUPERIOT applications identified for each demonstrator. For Demonstrator 1, the previously described applications are repeated in Table 26.

Table 27. Selected potential applications for demonstrator 1 (subset of Table 25).

Demonstrator	Potential Application
#1	1.2 - Smart tags incorporated in sensitive items
	1.4 - Tags specifically designed for logistic operations
	1.5 - Enhanced label for batch manufacturing
	1.6 - Tags incorporated in shelves or in other small product packages
	1.7 - Tags and labels for healthcare patients
	2.1 - Sensors and actuators for smart buildings
	2.2 - Sensors and actuators for construction monitoring
	2.3 - Sensors for medical and safety applications
	2.4 - Sensors and actuators applied to smart cities
	3.1 - Secure and private IoT communication
	3.2 - Reliable IoT communication

The potential applications of the first scenario (1.x) are derived from the idea of future smart tags and labels for identification and traceability of objects (static or moving) and people, with enhanced functionality. Some of these applications are currently accomplished with existing technology, such as QR codes, RAIN RFID, near-field communication (NFC), etc. However, these technologies are in many ways far from the vision of SUPERIOT, not only technology wise, but also on their sustainability.

Applications of scenario 2 (2.x) are linked to the idea of sustainable and inexpensive devices that can be deployed in large scale for environment sensing and actuation. This idea of large-scale sensing and actuation is a trending topic for low-power wide area network (LPWAN) technologies. Self-deployable networks like LoRaWAN or networks available from communication operators like Narrowband IoT (NB-IoT) and SigFox are already enabling large-scale sensing and actuation. Again, these technologies are in many ways far from the SUPERIOT vision, and one of the major issues is the number of batteries that need to be used and disposed for the operation of these technologies. Reconfigurability is also a distinctive feature of the SUPERIOT concept, allowing to dynamically change the characteristics of the system according to the needs, type of application or scenario. As an example, the system can decide if connectivity will use radio or optical communication technology.

Finally, applications from scenario 3 (3.x) may be seen as enhancements for IoT communication in general. In this sense, these topics may be seen as improvements to the current technologies being used in the different applications, or the other SUPERIOT applications from scenarios 1 and 2. As such, in what follows we focus our discussion on applications belonging to scenarios 1 and 2.

6.3.2 Existing solutions and SUPERIOT opportunities

To be able to identify the most interesting SUPERIOT opportunities, Table 27 describes the most common technologies of the existing solutions for each application.

Table 28. Existing solutions for each application of demonstrator 1.

Potential Application	**Technology of Existing Solutions**
1.2 - Smart tags incorporated in sensitive items	High frequency (HF) RFID (NFC) labels; Ultra-high frequency (UHF) RFID (RAIN RFID) labels.
1.4 - Tags specifically designed for logistic operations	HF RFID (NFC) labels; UHF RFID (RAIN RFID); GPS cellular trackers; GSM trackers.
1.5 - Enhanced label for batch manufacturing	Ultra-wideband (UWB) tags; Bluetooth Low Energy (BLE) tags. (both with e-ink display)
1.6 - Tags incorporated in shelves or in other small product packages	Electronic Shelf Labels (ESLs)
1.7 - Tags and labels for healthcare patients	Tyvek bracelets with barcode/QR code; UHF RFID (RAIN RFID) labels.
2.1 - Sensors and actuators for smart buildings	Sensors with different communication technologies: Wi-Fi; BLE; ZigBee; LoRaWAN; NB-IoT.
2.2 - Sensors and actuators for construction monitoring	Sensors (strain, accelerometers, displacement, tiltmeters) using wireless personal area network (WPAN) (Wi-Fi, BLE, Zigbee) cellular networks, satellite, LPWAN (LoRaWAN, NB-IoT).
2.3 - Sensors for medical and safety applications	Wi-Fi or BLE-enabled or inertial motion sensor-based wearable devices (e.g., to detect fall detection amongst the elderly), smart fitness watches, IoT-enabled devices for remote patient monitoring (e.g., vital sign monitor).
2.4 - Sensors and actuators applied to smart cities	Traffic flow sensors and smart traffic lights, license late recognition, GPS, RFID sensors, building management systems (e.g., to control heating, ventilation, air conditioning, etc.).

Even though many different applications are described, most of the existing solutions use a restricted group of communication technologies. Based on the previous table, solutions may be grouped in the following technologies:

- Optical readings (barcode/QR code)
- HF RFID (NFC) labels
- UHF RFID (RAIN RFID) labels
- Electronic Shelf Labels
- Wi-Fi tags, sensors and actuators
- WPAN tags, sensors and actuators (BLE, ZigBee, UWB)
- LPWAN tags, sensors and actuators (LoRaWAN, NB-IoT, SigFox)
- GPS trackers
- GSM trackers

Table 28 shows a qualitative comparison between the different technologies, considering relevant aspects of IoT technology addressed by SUPERIOT. In this table, besides the quantitative information on each parameter, we have defined three qualitative levels that help create a visual insight on the current status of each technology: green means that the technology has already a good performance in that specific characteristic; yellow means that it is not as good as other technologies, but there are situations where it is still acceptable; red means that it is a problem in many situations and there is a large space for improvement. Both the quantitative and qualitative analysis was based on the experience of the industrial partners of the project.

Requirement	Optical labels (barcode/QR code)	NFC labels	RAIN RFID labels	Electronic Shelf Labels	Wi-Fi tags	WPAN tags (BLE, ZigBee, UWB)	LPWAN tags (LoRaWAN, NB-IoT)	GPS Trackers	GSM Trackers
Reliability in different operational environments (dual-mode communication)	Needs manual scanners or passage points	Needs gates or passage points	Needs gates or passage points	Works with dedicated infrastructure (indoors or outdoors)	Works with dedicated infrastructure (indoors or outdoors)	Works with dedicated infrastructure (indoors or outdoors)	May work with existing infrastructure, but only radio comm	Only outdoors	Works with existing infrastructure, but only radio communication
Security and privacy (dual-mode communication)	Unique identifier, but typically no encryption	Advanced Encryption Standard (AES)	Cryptographic algorithms like AES	Encryption such as AES	Wi-Fi Protected Access (WPA) /WPA2/WPA3 protocols which include encryption	WPANs typically use encryption such as AES-CCM	Typically use AES-128 or RSA encryptions	AES-based encryption	GSM (2G) typically uses A5/1, A5/2 or A5/3 encryption
Reconfiguration capabilities (RIOT)	Not possible	Possible to reconfigure label encoding	Possible to reconfigure label encoding	Possible to reconfigure e-ink display remotely and other comm params	Possible to reconfigure information and comm params	Possible to reconfigure information and comm params	Possible to reconfigure information and comm params	Possible to reconfigure information and comm params	Possible to reconfigure information and comm params
Price (printed electronics)	Below one cent	Cents of Euros	Cents of Euros	Tens of Euros	Tens of Euros	Tens of Euros	Tens of Euros	Tens of Euros	Tens of Euros
Form factor (printed electronics)	Sticker-like	Similar to barcode label (sticker-like)	Similar to barcode label (sticker-like)	Similar to watch size (minimum)	Similar to watch size (minimum)	Similar to watch size (minimum)	Similar to watch size (minimum)	Similar to watch size (minimum)	Similar to watch size (minimum)
Position accuracy (dual-mode localization)	Proximity reading	Only presence detection (up to some decimeters)	Only presence detection (up to some meters)	Only presence detection	< 15 m	Between some decimeters and some meters	Tens to hundreds of meters	~ 10 m	Hundreds of meters
Sensing capabilities	Not possible	Only when powered by the reader	Only when powered by the reader	Not common, but possible	Different sensor possibilities	Different sensor possibilities	Different sensor possibilities	Different sensor possibilities	Different sensor possibilities
Actuating capabilities (namely display)	Not possible	No	No	Updatable e-ink display	Updatable e-ink display or other general purpose input/output (GPIO)	Updatable e-ink display or other GPIOs are possible	Updatable e-ink display or other GPIOs are possible	Not common, but possible	Not common, but possible
Lifetime (energy consumption and energy harvesting)	No battery	Magnetic coupling, no battery	Backscatter, no battery	Some years in normal operation	Some months in normal operation	Some years in normal operation	Some years in normal operation	Some months in normal operation	Some months in normal operation
Frequency of communication (energy consumption and energy harvesting)	Communication initiated by the reader	Communication initiated by the reader	Communication initiated by the reader	Twice per day in normal operation	Seconds or minutes	Seconds or minutes	Small number of communications per day (up to 10)	Small number of communications per day (up to 10)	Small number of communications per day (up to 10)
Reusable (printed electronics and sustainability)	Not possible, not reconfigurable	Difficult to reuse	Difficult to reuse	Reusable (batteries need to be recharged/ changed periodically)	Reusable (batteries need to be recharged/ changed periodically)	Reusable (batteries need to be recharged/ changed periodically)	Reusable (batteries need to be recharged/ changed periodically)	Reusable (batteries need to be recharged/ changed periodically)	Reusable (batteries need to be recharged/ changed periodically)
Recyclable/Disposable (printed electronics and sustainability)	Recyclable (paper)	No, even though there are no batteries involved	No, even though there are no batteries involved	Operates with batteries (not possible to recycle or easily dispose)	Operates with batteries (not possible to recycle or easily dispose)	Operates with batteries (not possible to recycle or easily dispose)	Operates with batteries (not possible to recycle or easily dispose)	Operates with batteries (not possible to recycle or easily dispose)	Operates with batteries (not possible to recycle or easily dispose)

Table 29. Comparison between different technologies used in the applications relevant to demonstrator 1.

Looking at the comparison table, there are already solutions with interesting functionalities, such as sensing and actuating capabilities, reconfigurability and location. However, most of these capabilities come with the need of a conventional recharging or one-use battery. This poses an immediate pricing problem, but mostly it leads to high recurring maintenance costs and environmental unsustainability.

When looking only at solutions that do not need conventional batteries (optical and passive RFID labels), the number of functionalities is strongly reduced. Communication is strongly limited, sensing and actuating capabilities are practically inexistent, and only presence detection is usually attainable. Even in these more sustainable solutions, there is no holistic approach for sustainability, from production until the end of the life of the product. These solutions are not easily recyclable or disposable and their usage on a large-scale will have a negative impact on the environment.

For this reason, there is an interesting opportunity for SUPERIOT to demonstrate an autonomous and reusable solution that can attain functionalities similar to the active (battery) solutions described in the table. As an example, there is currently no solution that can operate autonomously and simultaneously communicate data over long distances or provide something more than just presence detection.

Another relevant topic is the absence of light communication in every solution. Most of the solutions need dedicated infrastructure, and this also poses cost and sustainability issues. SUPERIOT dual-mode communication may be used to leverage existing infrastructure in different scenarios and dynamically adapt to different constraints.

6.3.3 Types of environments

The type of environment where each application is applied plays an important role when defining requirements. For this purpose, the list of potential applications was mapped to the most common types of environments where they are used. Table 30 maps the different applications to the most common environments.

Table 31 summarizes the different types of environments considered and their most relevant characteristics.

Table 30. Types of common environments of each potential application of demonstrator 1.

Potential Application	Types of Environments
1.2 - Smart tags incorporated in sensitive items	Store; Supermarket; Outdoor Transportation
1.4 - Tags specifically designed for logistic operations	Warehouse; Outdoors.
1.5 - Enhanced label for batch manufacturing	Factory.
1.6 - Tags incorporated in shelves or in other small product packages	Supermarket; Warehouses; Repositories; Outdoors.
1.7 - Tags and labels for healthcare patients	Hospitals; Primary Care Centers
2.1 - Sensors and actuators for smart buildings	Office; Hospital.
2.2 - Sensors and actuators for construction monitoring	Indoors/Outdoors.
2.3 - Sensors for medical and safety applications	Hospitals; Primary Care centers
2.4 - Sensors and actuators applied to smart cities	Outdoors.

Table 31. Relevant characteristics of the most common environments of demonstrator 1 applications.

Types of Environments	Radio communication coverage area	Energy Harvesting sources	AP deployment height	AP deployment density
Factory	Large indoor spaces with potential complex layouts Network: Local Area Network (LAN)	Solar energy, ambient light, energy from other nodes	Max ceiling height (3m-10m) Aps should be strategically placed at various heights to ensure coverage across different areas of the factory floor.	Require dense deployment of APs for reliable coverage
Hospital	Varied indoor spaces (patient rooms, hallways, operating rooms) Network: LAN for critical areas and wide area network (WAN) for hospital-wide coverage to connect various departments and buildings.	Solar energy, ambient light, energy from other nodes	Ceiling height (approx. 3m)	Medium to high density, particularly in critical care areas.
Office	Medium sized indoor spaces. Network: LAN	Solar energy, ambient light, energy from other nodes	Ceiling height (approx. 3m)	Moderate deployment density, considering office layout and user density
Outdoors	Open outdoor areas with potential obstructions like trees, buildings, etc. Network: WAN	Solar energy	Deploy Aps on tall structures like poles, buildings	High density for wide coverage
Store	Medium sized indoor spaces. Reliable coverage required for tracking products and monitoring inventory. LAN for the store premises, potentially interconnected through WAN for chain-wide communication and inventory management.	Solar energy, ambient light, energy from other nodes	Ceiling height (approx. 3m)	Moderate density
Supermarket	Potentially larger coverage area than a store. LAN within the supermarket, potentially interconnected through WAN for communication with suppliers and inventory management.	Solar energy, ambient light, energy from other nodes	Ceiling height (approx. 3m to 10m)	Medium to high density
Warehouse	Large indoor spaces. Comprehensive and reliable coverage is essential for inventory management and logistics. LAN within the warehouse, and potentially WAN for communication with other facilities or logistic networks.	Solar energy, ambient light, energy from other nodes	Ceiling height (approx. 10m)	High deployment density

6.3.4 Selection of the most relevant applications for Demonstrator 1

In this section, a further selection of the most relevant applications is performed for Demonstrator 1, taking into account the project's objectives and concept, and also the capability of performing them in a demonstration environment.

Figure 1 presents the summary objectives/concept of SUPERIOT. One of the key points of the project is to exploit the coexistence of radio and light technology. This applies to communication, energy harvesting, and positioning. Taking this into account, the demonstrations will need radio and light functionality in the nodes and network. This poses challenges in both the communication range and the infrastructure setup, especially for the case of optical communications, since these are more sensitive to obstacles. For that reason, applications that do not include outdoor scenarios are preferable for the demonstration of the SUPERIOT concept. Looking at Table 27, applications like smart tags incorporated in sensitive items, and sensors applied to smart cities or construction monitoring, assume a relevant part of their use cases in outdoor settings, making them less attractive for the final demonstrators of the project.

Another important point in the project is to demonstrate the SUPERIOT capability of positioning. This feature is particularly relevant in applications where node mobility is expected. This means that applications where nodes are stationary are not as relevant as the applications that consider moving nodes. The potential application of having tags incorporated in shelves would not be as relevant to the SUPERIOT concept as other potential applications. The same applies to the sensors and actuators for smart cities and construction monitoring, since many use cases imply stationary nodes. Moreover, since Demonstrator 2 focuses on medical ICT scenarios, the applications related to medical scenario are not a priority for Demonstrator 1.

Based on this analysis, the following table highlights the selected most relevant applications for demonstrator 1.

Table 32. Most relevant applications for demonstrator 1.

Demonstrator	Relevant Application
#1	1.4 - Tags specifically designed for logistic operations
	1.5 - Enhanced label for batch manufacturing

6.3.5 Use cases and functional requirements

In this section, two examples of use cases are described, and the corresponding functional requirements are derived. As mentioned before, the use cases specified are not meant to be necessarily the use cases to be demonstrated in the project, they are just examples to help define ranges of values for the requirements that can be seen as guidance for the development of SUPERIOT technology.

Considering real-life application(s) of the smart tags and labels, we can derive their use case(s). Hence, depending on the particular use case, we can formulate the real-life requirements to help shape the SUPERIOT system and its properties. Consequently, we can introduce the demo application(s), demo use case(s) and demo requirements, that correspond to their real-life counterparts, and shape the demo SUPERIOT system and its demo-scale properties. Demo requirements focus on the essential properties of the SUPERIOT project, focusing on the presentation of developed technologies within the SUPERIOT consortium. These relationships are shown in Figure 15.

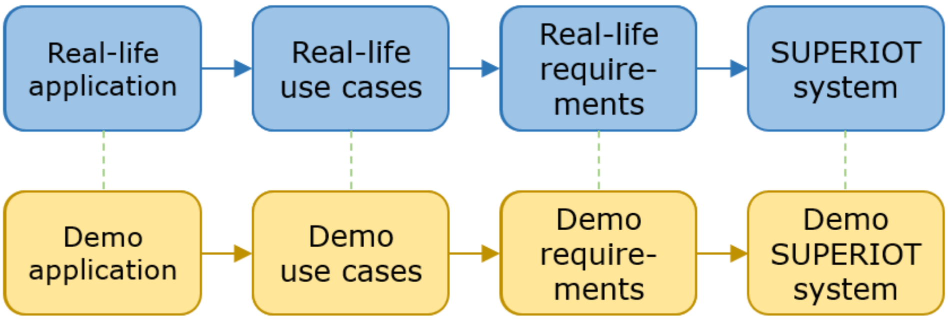


Figure 15. Applications, use cases and requirements and their relationships with the SUPERIOT system and demonstrators.

In the present document, we focus on the requirements for the real-life use cases. As mentioned, this can be seen as guidance for the development of SUPERIOT technology. However, for the demonstration of such use cases, we will define demo-scale examples to illustrate these use cases. When these demo-scale examples are defined later in the project, we will tune the requirements needed for that specific demonstration.

6.3.5.1 Use case example 1: industrial material flow

Overview

The first example of use case consists of real-time asset tracking in an industrial scenario. During manufacturing and internal logistics, operators and managers need full visibility on the current location and status of their products. This is very important so that operators do not lose time searching for goods, and processes keep flowing as efficiently as possible. Managers also need a transparent way of knowing the currents status of production and use quality data to analyze past events and make better decisions for the future. The goods that need to be tracked include production orders, batches, or even raw material or pallets of finished goods.

Nowadays, movements and location of goods in production are mainly achieved using manual scanning and their status and information is normally checked using a paper attached to the goods. This is an error-prone process that impacts production processes, search times, and visibility. The usage of disposable paper is also not sustainable on a large scale.

Passive RFID or active RFID tags can be used to automate the movements and processes inside the facility and gain more visibility on production. However, as shown on the previous comparison table, passive RFID is not able to provide accurate location - only presence detection, and there is no possibility of changing the displayed information. Active RFID can provide both accurate location and an updatable display, but they need conventional batteries, making them difficult to maintain and not sustainable on a large scale.

In this use case example, the SUPERIOT smart tag/label may be used to identify and track the different goods in production. The SUPERIOT smart tag/label would enable accurate tracking using the dual-mode (light/radio) localization, enabling the automatic movements between stages and full visibility on production. The SUPERIOT smart tag/label display could be used to display the identification of the product and their updated status. Moreover, eliminating the need to use batteries would lead to a more cost-effective and sustainable solution. Information to or from the smart tag can be wirelessly transmitted using radio, light or eventually both, depending on the requirement of the connection, type of environment, etc.

Description

Following the above discussion, we can consider the real-life application in the form of smart tags and labels applied for the industrial manufacturing of e.g., electric motors. Next, we can derive the particular real-life use case that will allow us to emerge the requirements placed on the SUPERIOT system and its properties. Such a real-life use case is formulated as a simplified, yet based on partners experience, production process. The actors involved in the use case are Operator, Quality Engineer, Production Manager and Customer. The unit is subjected to the process of production before it becomes a product. The product is an electric motor. The use-case is implemented in steps from 1 to 5. Activities may result in success (OK) or failure (NOK). The OK status results in proceeding with the steps. The NOK status is handled and neutralized.

Following the real-life use case implemented in steps from 1 to 5, we can cast it onto the corresponding demo use case. The actors involved in a possible future demo use case are the same but played by the presenters and the recipients of the demo presentation. The unit (product) is subjected to the processes reflected in a model scale. The product is a model of an electric motor or electric motor of appropriately small size. The times, distances and working stations dimensions will be adjusted accordingly to the demo scale for the needs of the demo presentations but remaining full-scale capabilities.

- Step 1: Attach tag to unit
    - Operator attaches tag to a couple of ten centimeters unit. The tag has a form that is easy for the operator to handle and of a size that doesn’t affect the production.
    - Operator verifies the operation of attaching the tag to the unit
        - OK: Operator proceeds with the step
        - NOK: Operator repeats or corrects the operation of attaching the tag to the unit
    - Routing information shown on the display of the tag

- Step 2: Process the unit
  - Operator routes the unit at a distance of 4 meters to subsequently optimal workstations according to the information shown on the display – optimization is shown in Figure 16. The distance between each workstation is 4 meters. Each workstation has dimensions of 2 m by 2.4 m. The free space around the edge of each station covers 0.9 m. All stations are located in a common hall, 4 meters high.
    - OK: Operator proceeds with the step
    - NOK: Operator follows the routing information on the display - e.g.:
      - "WS2 is too busy. Route this item to WS5."
      - "Do not route. Too much acceleration was recorded. Wait for Quality Engineer action."

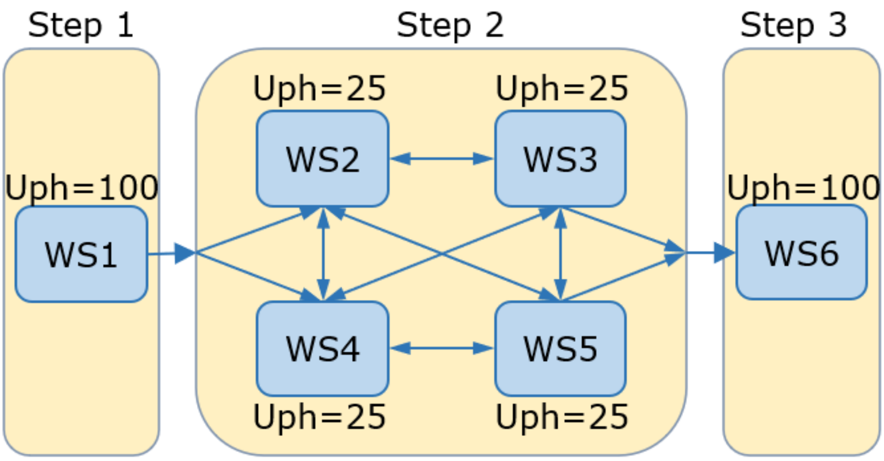


Figure 16. Illustration of directing the item between workstations (WS) whose availability depends on their throughput specified in units per hour (UPH) – optimization of step 2.

At the WS2, it may be needed to use VLC offered by the SUPERIOT node instead of RF communication. At this workstation, machining work is performed using a lathe drove by an electric motor powered by a converter. The lathe also uses electrical signals from the encoder to control its drive. RF communication of the IoT node could be disturbed by the rotating magnetic field of the motor (of the order of hundreds of Hz) and high carrier frequency of the converter (of the order of kHz). The RF communication signal could also interfere with the encoder electric signals needed for precise drive control. The VLC would prevent the electromagnetic compatibility (EMC) problems between IoT node and WS2.

At the WS3, it may be also needed to use VLC offered by the SUPERIOT node instead of RF communication. At WS3, machining work is performed using a 3D computer numeric control (CNC) milling machine equipped with electric drives consisting of electric motors and voltage and frequency converters. RF communication of the IoT node could be disturbed by the rotating magnetic field of the motor and the high carrier frequency of the converter. The RF communication signal could also interfere with the CNC machine control signals. The VLC would also prevent the EMC problems at WS3.

- Step 3: Painting the unit
  - Operator routes the unit at a distance of 15 meters to the painting and curing workstation. The painting and curing workstation have dimensions of 6 m by 2.4 m. The free space around the edge of the station covers 0.9 m.

        - OK: Operator proceeds with the step
        - NOK: Operator follows the information on the display - e.g.:
            - "Do not route. Too much acceleration was recorded. Wait for Quality Engineer action."
            - "Do not route. Too low temperature during painting. Wait for Quality Engineer action."
            - "Do not route. This item was moved during painting. Wait for Quality Engineer action."
            - "Do not route. Too high temperature during curing. Wait for Quality Engineer action."
            - "Do not route. Too high humidity during curing. Wait for Quality Engineer action."
            - "Do not route. This item was moved during curing. Wait for Quality Engineer action."
    - Routing information shown on the display – e.g., "Curing time elapsed. Route this item to WS6."

      Due to the painting process, at least the display, the photovoltaic (PV) panel and the VLC receiver, or the entire IoT node, must be covered. This means that RF communication is required for this step and VLC may be temporarily unavailable during the painting process.
- Step 4: Testing the unit
    - Operator routes the unit at a distance of 15 meters to the testing workstation. The testing workstation has dimensions of 2.4 m by 2.4 m. The free space around the edge of the station covers 0.9 m.
        - OK: Operator proceeds with the step
        - NOK: Operator follows the information on the display – e.g.:
            - "Do not route. Too high temperature during curing. Wait for Quality Engineer action."
            - "Do not route. This item was moved during testing. Wait for Quality Engineer action."
    - Routing information shown on the display

      At the testing workstation, it may be desirable to use VLC offered by the SUPERIOT node instead of RF communications. At this workstation, the mechanical and electrical properties of the unit are measured to be evaluated. These measurements are mostly based on electrical signals. At the same time, the electric motor is powered by a voltage and frequency converter and operates by generating a rotating magnetic field and the drive generates unwanted electromagnetic interferences. RF communication of the IoT node might be disturbed by the rotating magnetic field of the motor and electromagnetic interference resulting from the power supply of the converter with a high carrier frequency of the order of kHz. At the same time, the RF communication signal itself could interfere with the measurement signals recorded at the station. The introduction of VLC would prevent these problems of electromagnetic interference between IoT node and testing workstation.
- Step 5: Packing and storage product

- Operator routes the unit at a distance of 5 meters to the packing and at a distance of 15 meters to the storage. The packing area has dimensions of 2.4 m by 3 m. The storage area has dimensions of 12 m by 12 m.
    - OK: Operator proceeds with the step
    - NOK: Operator follows the routing information on the display - e.g.:
        - "Do not route. Too much acceleration was recorded. Wait for Quality Engineer action."
- Properties information shared with the Quality Engineer, Production Manager and Customer – e.g.:
    - "Available stock: 15 000 pcs"
    - "Product S/N: 202304101101: too much acceleration."
    - "Product S/N: 202304101101: too high temperature."
    - "Product S/N: 202304101101: too high humidity."
    - "Product S/N: 202304101101 has left the warehouse and is on its way to the customer."

According to the use case description, the real-life requirements that shape the SUPERIOT system with its properties can be formulated.

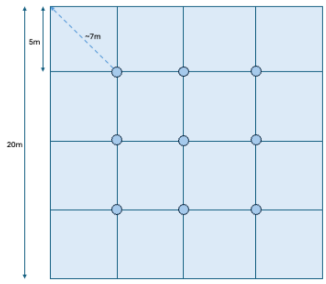
Functional requirements

Table 31 lists some important functional requirements derived from the description of the use case. Research partners with different technology backgrounds were involved to help define the expected values for each requirement. Industrial partners also contributed with their experience on similar use cases.

Table 33. Functional requirements derived for use case example 1: industrial material flow.

Requirement	Expected value (Range)	Comments
Data rate in downlink (DL)	Radio: from 125 kbps to 2 Mbps. VLC: up to 100 kbps depending on the light-emitting diode (LED) and photodiode (PD).	Bluetooth® 5: 2 Mbps, 1 Mbps, 500 kbps, and 125 kbps IEEE 802.15.4-2006: 250 kbps Proprietary 2.4 GHz: 2 Mbps, 1 Mbps The expected range of radio communication values for the uplink can go from 125 kbps to 2 Mbps, based on the BLE capabilities. For most of the operation scenarios in the motor manufacturing, the labels will just receive some messages to reconfigure their operation, or even trigger some specific sensing capabilities. However, to be able to update the e-ink display, there may be some situations where higher data rates are needed for the radio. Radio: Considering the BLE radio communication supported by Bluetooth 5, including the format and length of the data packets, excluding the packets loss, the useful payload versus the complete transmission period results in the following throughputs at considered data rates: 1.4 Mb/s (@2Mbps), 0.8 Mb/s (@1Mbps), 0.4 Mb/s (@500kbps), 0.1 Mb/s (@125kbps). The Demo1 used e-ink 2.13" 250 x 122 pixels display can be fed with up to 30500 bits of data. Such amount of data results in the following estimated data transmission times at considered data rates (excluding the packets loss): 22 ms (@2Mbps), 38 ms (@1Mbps), 76 ms (@500kbps), 305 ms (@125kbps). Each of this transmission time is reasonable considering the e-ink display refresh time of 300-2000 ms. However, higher data rates, such as 1Mbps and 2 Mbps could be needed to mitigate the throughput decrease resulting from the data packets loss due to the presence of noise and interference. VLC: Considering the optical communication with the use of NEC protocol and sending the payload in 8-bit command length slot of NEC data frame, the throughput for the optical communication is only 0.11 kb/s. Such throughput is not optimal for sending full e-ink display data, as the time would be of 260 seconds. The optical communication is considered to send and display on the e-ink display urgent information, e.g., two bytes, in a reliable manner by means of light. The payload of two bytes results in the estimated data transmission time of 136 ms. Such transmission time for urgent communicates is reasonable considering the e-ink display refresh time.
Data rate in uplink (UL)	Radio: from 125 kbps to 2 Mbps. VLC: up to 10 kbps depending on the LED and PD.	Since the labels for motor production will be used in a controlled environment (factory), where energy sources can even be added, if needed, we expect that they may be needed in the future for a more real-time monitoring of production, namely in test phases, where the amount of sensing data can be larger than for other use cases. This is the reason why it can be interesting to extend the needs of data rate to the upper end of the BLE capability.

Frequency of signaling in DL	Min: 1 msg/hour Max: 1 msg/min	How often the node needs to be connected (e.g., every x min, continuously, etc.) The updates of the display will be linked to position updates, and sensing information. This means that updates of the display between some minutes, up to one hour will be enough to accomplish most of the value of the use case (please refer also to the frequency of signaling in UL).
Frequency of signaling in UL	Min: 1 msg/hour Max: 1 msg/min	How often the node needs to be connected In industrial manufacturing scenarios like the one described (electric motor manufacturing), the products are not constantly moving between stations. Most of the times, the products will stay in the same station during several minutes or even hours. This means that it is usually enough to have updates on positioning between some minutes (when moving), up to one hour (when stationary). Regarding sensing (e.g., temperature, vibration) it is enough to have central visibility with the same update rate. If more detail is needed, the node could measure more frecuently and upload the complete set of values from time to time.
Reliability	99%	
Latency requirements	No major constraints	
Simultaneous operation of UL and DL	No	
Importance of dynamic reconfiguration	Medium	E.g., need for changing communication modes during operation
IoT node density	Up to 5/sqm (during production) Up to 20/sqm (when stored in warehouse)	During production, we expect to have from 1 to up to 5 motors per squared meter, depending on the size of the motors. In the warehouse, motors can be stored in vertical racks. We consider that the typical maximum of possible rack heights will be 4m, which leads to a maximum of 20 motors per squared meter.
Mobility of nodes/objects	Yes	
Node autonomy	Yes	Required operating time without energy harvesting
Wireless range	Up to 10 meters	This value is based on the typical maximum height of ceilings in industrial scenarios. This range may be easier to manage with radio communication than with VLC. Thus, in scenarios where 10 meters are needed, radio may be the preferred technology, and VLC may be used when the node is closer to the gateway. In situations where communication and location is critical, and the height of the ceiling is high, the gateways may be installed closer to the nodes (pillars, walls, or other structures), instead of installing them closer to the ceiling.

Expected localization accuracy in range	Less than 50 cm	Using BLE and VLC
Expected localization accuracy in angle	5 degrees	Depends on number of antennas
Expected localization accuracy in position	Less than 30 cm	Using BLE and VLC
Localization update rate	1 per 10 seconds	
Density of APs	9 APs per 400 square meters	In localization topics, APs are sometimes referred to as localization anchors. The majority of nodes will be at a maximum horizontal distance of 3.5 meters, which offers high SINR and ambient energy for both optical/RF communication and energy transfer, respectively.  The number of APs is set to 9 to ensure sufficient communication and energy-transfer resources as well as to minimize the geometric dilution of precision for node localization.
Expected average level of illumination in the environment (Lux) required by the node to operate	Min: 200 lux Max: 700 lux	
Sensors on board **Always on?**	No	
Actuators on board **Always on?**	No	
Data processing on node	Yes	
Modes of operation (as supported by System-on-a-Chip (SoC))	Active mode Idle/standby mode Sleep mode	The active mode represents the highest power consumption scenario, where all components operate at peak demand. This includes the nRF52833 BLE SoC, narrow-band VLC receiver (RX) and transmitter (TX), environmental sensor, and the E-ink display.
Radio transmission power	-20 dBm to +8 dBm, configurable in 4 dB steps	-95 dBm sensitivity in 1 Mbps BLE mode -103 dBm sensitivity in 125 kbps BLE mode (long range)
Power source	Micro-supercapacitor storage for hybrid node and simultaneous wireless information	

	and power transfer (SWIPT) for energy harvesting	
Energy/Power consumption and storage requirements	Case 1 (1 hour cycle): Average node's current consumption = 2.3 mA, Energy = 27 J/cycle Minimum supercapacitor size to sustain active operations in one cycle= 6 mF. Case 1 (1 min cycle): Average node's current consumption = 2.4 mA, Energy = 0.5 J/cycle Minimum supercapacitor size to sustain active operations in one cycle = 6 mF. Case 2 (1 hour cycle): Average node's current consumption = 0.01 mA, Energy = 0.12 J/cycle Minimum supercapacitor size to sustain active operations in one cycle = 14 mF. Case 2 (1 min cycle): Average node's current consumption = 0.3 mA, Energy = 0.06 J/cycle Minimum supercapacitor size to sustain active operations in one cycle = 14 mF.	Case 1: All node functionalities enabled (BLE, NBVLC, Sensing, E-ink) in an operation cycle. The node does not sleep at any point in time during its operation cycle. It remains connected to a central device (e.g. gateway) throughout its whole operating period (considering a maximum BLE TX power level). The supercapacitor charges during idle period in the operation cycle. Case 2: Node's operations include startup state (due to wake-up), sensing and E-ink displaying, and deep sleep in one cycle, which is repeated every 1 hour or 1 min (VLC and BLE both off). The supercapacitor charges during deep sleep period in the operation cycle.
Scalability	The solution should be able to scale to thousands of nodes and tens of thousands of squared meters in terms of infrastructure. Reusability of labels is an important point when scaling the solution.	In large factories, we expect that thousands of motors can be produced at the same time. The system will be scalable, i.e., able to handle a growing amount of work, by means of increasing the numbers of nodes and, if needed, also gateways connected to the network.

6.3.5.2 Use case example 2: logistics and distribution

Overview

Location, traceability, and sensing play a crucial role in the efficient functioning of logistics and distribution scenarios. However, there are several current challenges that make this continuous monitoring of packages and other goods very difficult to achieve, namely:

- Complex supply chains involving multiple intermediaries, modes of transportation and handoffs
- Operating of companies on a global scale, making it difficult to have communication in all parts of the supply-chain or even other types of information
- Data security and privacy of communications

Current solutions either rely on simple labels (e.g., barcode, QR code, RFID) that only identify and track goods via manual scanning or reading gates, or on expensive and battery-powered trackers (e.g., GPS/GSM trackers), that need to be managed and reused somehow.

SUPERIOT smart label/tag with dual-mode communication and localization, sensing and actuating capabilities, while still operating with non-conventional batteries, can really change the way logistics and distribution handle and monitor the packages and other goods. The reconfigurability of the proposed SUPERIOT node can be used to respond to the current complexity and different environments of the supply chains, not only when packages are in transit, but also when they are stored in warehouses. Dual-mode (RF, VLC) communication can be used to address security, privacy and reliability issues and enable different types of options for communication along the supply chain.

Another important aspect of logistics and distributions is the capability of guaranteeing the necessary conditions of the goods during their transportation and storage. One known example of this is the cold-chain logistics, where goods need to be kept in a certain range of temperatures to ensure their quality is not compromised. Nowadays, the sensing strongly depends on powered sensors, namely sensors attached to the trucks or containers moving the goods. However, with SUPERIOT technology, this could be done without the need of conventional batteries, making it more versatile and scalable. Actuating capabilities, such as the visual display, could also be used to give information about the conditions of goods.

Description

Following the above overview, we can consider the real-life application in the form of smart tags and labels applied for the logistics and distribution of e.g., vaccines. Next, we can extract the real-life use case to recognize the requirements placed on the SUPERIOT system. The formulated and considered use case is a simplified logistics and distribution process, based on partners' experiences. The actors involved in the use case are Operators, Drivers, Health Workers, Quality Engineer, Supportive Supervisors, Supply Managers, Global Supply Manager, and Vaccinated Person. The vaccination vial is subjected to the cold-chain logistics and distribution process before the vaccine is unpacked and administered to the vaccinated person. For the use of this example, we assume that different vaccines can be stored at room temperature no more than e.g., 30 minutes, 2 hours, or 6 hours. Even though there are many other quality assurance challenges during the logistics process of vaccines (e.g., sunlight exposure, hermitization, etc.), we focus this use case in the cold-chain assurance, i.e., ensuring that the temperature of vaccines is kept within the defined limits. At a temperature of 2-8°C these periods are up to 5 days, 6 hours, and 30 days, respectively. These periods concern three different vaccinations and are given as examples. The use case is implemented in steps from 1 to 6, as described below. Activities carried out within a given step may result in success (OK) or failure (NOK). The OK status results in proceeding with the activities consistent with the normal step routine. The NOK status is handled and neutralized consistently with the failure step routine.

Following the real-life use case implemented in steps from 1 to 6, we can work out a demo use case from it. The actors of main roles involved in a demo use case are the same but played by the presenters and the recipients of the demo presentation. The vaccine is subjected to the logistics and distribution processes reflected in a model scale. The times, distances, and logistic stations dimensions will be adjusted accordingly to the demo scale for the needs of the demo presentations but remaining full-scale capabilities.

- Step 1: Verify the tag attached to the vaccination vial
    - The tag is automatically attached to the vaccination vial during the manufacturing process. The tag has a form that is easy for the actuator to handle and of a size that doesn't affect the logistics and distribution.
    - Operator verifies the operation of attaching the tag to the vials contained in the collective packaging comparing the cold-chain maintenance information and temperature chart indicator available on stationary industrial monitors – e.g.:
        - OK: Operator proceeds with the step
        - NOK: Operator calls a Quality Engineer. The Quality Engineer prepares a report and passes the vial for rejection or re-attaching the tag.
    - Cold-chain maintenance information, localization information, and temperature chart indicator are available on stationary industrial monitor for the Operator and online for Supply Managers from the authorized accounts. Automatic real-time

alerts for the Operator and Supply Managers are also defined to be able to act before vaccines get damaged (e.g., understand that the temperature is close to the acceptable limit). The temperature logging is also stored to enable better decisions in the future.

- Step 2: Process the vaccines to the manufacturer's storage
    - Operator routes the collective vial packaging at a distance of 20 meters to a cold storage freezer located in a room to store the vaccines before a final lot release. The storage time may be up to several weeks. The freezer has dimensions of 1.2 m by 1.2 m and height of 2.4 m. The cold room has dimensions of 9 m by 12 m and height of 3 m. Depending on the vaccination, the freezing temperature can be between -25°C and -15°C or even between -80°C and -60°C.
        - OK: Operator proceeds with the step
        - NOK: Operator follows the routing information on stationary industrial monitors - e.g.:
            - "The cold chain has been broken for vial(s) S/N:20231009. Wait for Quality Engineer action."
            - "Too much acceleration was recorded. The vial(s) S/N:20231009 could be broken. Wait for Quality Engineer action."
- Step 3: Beginning of distribution
    - Operator takes the bulk packages of vaccine vials out of the freezer and routes them at a distance of 6 meters to a refrigerated truck. The standard dimensions of a refrigerated truck are internal width 2.45 m, internal height 2.65 m, internal length 13.4 m.
        - OK: Operator proceeds with the step
        - NOK: Operator follows the information on stationary industrial monitors - e.g.:
            - "The cold chain has been broken for vial(s) S/N:20231009. Wait for Quality Engineer action."
            - "Too low temperature during storage was recorded. Wait for Quality Engineer action."
            - "Too high temperature during storage was recorded. Wait for Quality Engineer action."
    - Driver scans the bulk packages of vaccine vials placed into the refrigerated truck.
    - Routing information shown on stationary industrial monitors - e.g., "Product placed correctly in the refrigerated truck. Confirm the start of the transport with the truck driver."
- Step 4: Long distance distribution
    - Truck driver delivers the bulk packages to the airport.
    - Airport crew packs the bulk packages to the freezing chamber on the plane.
    - The plane flies to its destination.
    - Airport crew unpacks the bulk packages from the freezing chamber on the plane and places them into the refrigerated truck.
    - Truck driver delivers the bulk packages to the regional store.
    - Regional store operator unpacks the bulk packages from the refrigerated truck arrived from the airport and places them to the refrigerated truck departing to the health center.

    - Truck driver delivers the bulk packages to the health center.

      Along the step 4, multiple external subcontractors (e.g., airlines) are involved in distribution. Distribution takes place over a very large area not covered by RF or VLC communication. The node must be energy-autonomous enough to record properties from sensors and the time of their occurrence in order to save the data and communicate exceedances after reconnecting to the SUPERIOT network.

- Step 5: Delivery the vaccines to the health center's storage
    - Health center operator unpacks the bulk packages from the refrigerated truck and routes them to the health center's cold storage freezer located in a room to store the vaccines. The freezer has dimensions of 1 m by 1 m and height of 2 m. The cold room has dimensions of 5 m by 6 m and height of 2.6 m. Depending on the vaccination, the freezing temperature can be between -25°C and -15°C or even between -80°C and -60°C. The tag reconnects to the SUPERIOT network.
    - Cold-chain maintenance information, localization information, and temperature chart indicator are available on stationary industrial monitor for the Operator and online for Supply Managers from the authorized accounts – e.g.:
        - "Product S/N:20231009: too much acceleration on 22/09/2023 at 2:32 PM."
        - "Product S/N:20231009: too high temperature on 22/09/2023 at 2:32 PM."
        - "Product S/N:20231009: too low temperature on 22/09/2023 at 2:32 PM."
        - "Product S/N:20231009: too high humidity on 22/09/2023 at 2:32 PM."
        - "Product S/N:20231009: too much light on 22/09/2023 at 2:32 PM. The box could have been opened and the vaccines could have been tampered."
- Step 6: Delivery the vaccines to vaccinator
    - Operator takes the vaccine vial(s) out of the freezer, places it(them) to a cold box and routes to a vaccine carrier. Cold-chain maintenance information, localization information, and temperature chart indicator are available on stationary monitor for the Operator and online for Supply Managers from the authorized accounts.
        - OK: Operator proceeds with the step
        - NOK: Operator follows the routing information on stationary industrial monitors - e.g.:
            - "Do not route. The cold chain has been broken for vial(s) S/N:20231009. Wait for the Local Supply Manager action."
            - "Do not route. Too much acceleration was recorded. The vial(s) S/N:20231009 could be broken. Wait for the Local Supply Manager action."
    - Health worker takes a cold box and vaccine carrier routes the vaccine(s) at a distance ranging from several kilometers to tens of kilometers by car, motorcycle, boat, animal (horse, donkey, camel), bicycle, foot, drone.

      Along the health worker route, areas may not be covered by RF or VLC communication. The node must be energy-autonomous enough to record properties from sensors and the time of their occurrence in order to save the data and communicate exceedances after reconnecting to the SUPERIOT network.
    - Vaccinator takes a cold box with a vaccine(s) and can start vaccinations. The tag reconnects to the SUPERIOT network via the vaccinator's smartphone. The cold-chain maintenance information and temperature chart indicator are available

online for Supply Managers from the authorized accounts and on the display of the vaccinator's smartphone (for vaccinator and for vaccinated person) – e.g.:

- "Product S/N:20231009: No exceedances. Vaccine stored under the required conditions"
- "Product S/N:20231009: too much acceleration on 23/09/2023 at 1:47 PM."
- "Product S/N:20231009: too high temperature on 23/09/2023 at 1:47 PM."
- "Product S/N:20231009: too low temperature on 23/09/2023 at 1:47 PM."
- "Product S/N:20231009: too high humidity on 23/09/2023 at 1:47 PM."
- "Product S/N:20231009: too much light on 23/09/2023 at 1:47 PM. The box could have been opened and the vaccines could have been tampered."

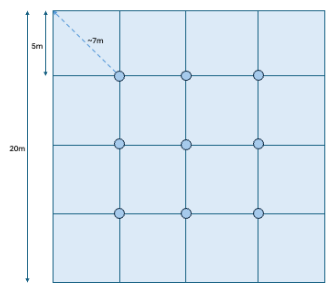
According to the use case description, the real-life requirements can be formulated, that shape the SUPERIOT system with its properties.

Functional requirements

To help define the functional requirements for this use case, research partners with different technology backgrounds were involved. Industrial partners also contributed with their experience on similar use cases.

Table 34. Functional requirements derived for use case example 2: logistics and distribution.

Requirement	Expected value (Range)	Comment
Data rate in DL	125 kbps	In this use case, the amount of energy available for harvesting can be very low (storage of vaccines inside boxes or inside freezers without light). At the same time, there may be situations where higher communication range is needed during the logistic process. For that reason, we will probably try to constraint the amount of data to be sent and received to a minimum (and the minimum data rate of BLE 5 is 125 kbps). Such considered BLE data rate is a reasonable optimum between the data transfer time and the energy consumption. The data rate 125 kbps provides enough data transfer time for the considered use case. In terms of optical communication, and taking into account its possible limitations, we will follow a best-effort approach in terms of data rates. The considered optical communication approach is to send the data in the form of operation command or urgent or sensitive information to be processed in the node, e.g., two bytes, in a reliable manner by means of the light.
Data rate in UL	125 kbps	See justification above (DL).
Frequency of signaling in DL	Min: 1 msg/day Max: 1 msg/min	How often the node needs to be connected (e.g., every x min, continuously, etc.)
Frequency of signaling in UL	Min: 1 msg/day Max: 1 msg/min	How often the node needs to be connected
Reliability	99.999% with a 95% level of confidence	The Food and Drug Administration recommends that value (99.999%) for e.g., emergency-use injectors. We need to check if it is needed for e.g., temperature tracking.

		However, the solutions existing on the pharma and logistics cold chain tracking provide the reliability somewhere in between 99 to 99.9999%
Latency requirements	No major constraints	
Simultaneous operation of UL and DL	No	
Importance of dynamic reconfiguration	Medium	E.g., need for changing communication modes during operation
IoT node density	Up to 350 000 per m^3	Based on World Health Organization estimates, a vaccine takes a storage space of 3 cm^3 per dose.
Mobility of nodes/objects	Yes	
Wireless range	Up to 4 meters	Considering that the nodes will communicate when they are in the storage areas and the ceiling height will not be typically larger than 3 meters.
Node autonomy	Yes	Required operating time without energy harvesting
Expected localization accuracy in range	Less than 200 cm	RFID and VLC
Expected localization accuracy in angle	15 degrees	Depends on number of antennas
Expected localization accuracy in position	Less than 100 cm	RFID and VLC
Localization update rate	1 per 10 seconds	
Density of APs	9 APs per 400 square meters	In localization topics, APs are sometimes referred to as localization anchors. The majority of nodes will be at a maximum horizontal distance of 3.5 meters, which offers high SINR and ambient energy for both optical/RF communication and energy transfer, respectively.  The number of APs is set to 9 to ensure sufficient communication and energy-transfer resources as well as to minimize the geometric dilution of precision for node localization.
Expected average level of illumination in the environment (Lux) required by the node to operate	Min: 200 lux Max: 700 lux	There may be periods of time in this specific use case and other use cases where the node will not be able to operate or communicate due to the low level of illumination. This should be

		taken into account for the different applications.
Sensors on board **Always on?**	Yes (temperature sensing)	Temperature sensor on-board always on for constant and reliable temperature monitoring.
Actuators on board **Always on?**	Yes	Small e-paper display, small flex e-paper display, or 7-segment e-paper display. It always shows the content but not always consumes the energy. The display is not always on (i.e., not always consumes the energy) – e.g., e-Ink only consumes power when the content changes.
Data processing on node	Yes	Data recording (e.g., temperature) when not connected to the SUPERIOT network (e.g. areas not covered by RF or VLC communication). Data pre-processing before recording or transmitting.
Modes of operation (as supported by SoC)	Active mode Idle/standby mode Sleep mode	Active mode as often as necessary and sleep mode as often as possible. With waking up, e.g. by a signal from the temperature sensor when the temperature changes.
Radio transmission power	-20 dBm to +8 dBm	
Energy/Power consumption and storage requirements	Case 1 (1 day cycle): Average node's current consumption = 2.3 mA, Energy = 640 J/cycle Minimum supercapacitor size to sustain active operations in one cycle= 6 mF. Case 1 (1 min cycle): Average node's current consumption = 2.4 mA, Energy = 0.5 J/cycle Minimum supercapacitor size to sustain active operations in one cycle = 6 mF. Case 2 (1 day cycle): Average node's current consumption = 0.01 mA, Energy = 1.5 J/cycle Minimum supercapacitor size to sustain active operations in one cycle = 14 mF. Case 2 (1 min cycle): Average node's current consumption = 0.3 mA, Energy = 0.1 J/cycle Minimum supercapacitor size to sustain active operations in one cycle = 14 mF.	Case 1: All node functionalities enabled (BLE, NBVLC, Sensing, E-ink) in an operation cycle. The node does not sleep at any point in time during its operation cycle. It remains connected to a central device (e.g. gateway) throughout its whole operating period (considering a maximum BLE TX power level). The supercapacitor charges during idle period in the operation cycle. Case 2: Node's operations include startup state (due to wake-up), sensing and E-ink displaying, and deep sleep in one cycle, which is repeated every 1 day or 1 min (VLC and BLE both off). The supercapacitor charges during deep sleep period in the operation cycle.
Scalability	Tens of millions of IoT nodes per year	It is estimated that tens of millions of vaccines are produce each year. The system will be scalable and able to handle a growing amount

	In terms of infrastructure for communication, the different cold supply chain warehouses need to be covered	of work, by means of increasing the numbers of nodes and gateways connected to the network, where server space also can be increased according to the demands.

6.4 Demonstrator 2 – Advanced Logistics in Medical ICT Scenarios

6.4.1 Demonstrator overview

This demonstrator focuses on a network-level demonstrator developed for advanced logistics in medical ICT scenarios. Behind this demonstrator there is also a future vision for a fully printed sticker-like autonomous reconfigurable IoT node with sensors, actuators, and connectivity functionalities. Besides enabling large-scale monitoring and management of medical tools and equipment, this opens a possibility for long-term health monitoring to follow the health condition of both healthy people and people with some medical conditions.

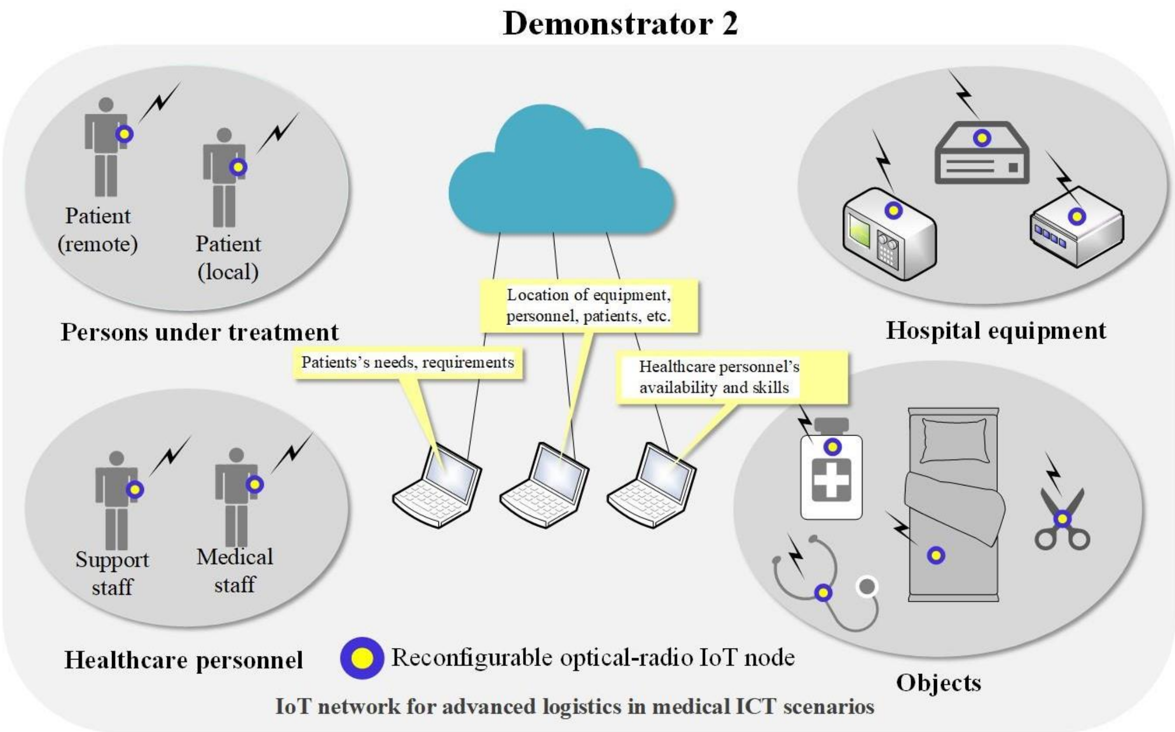


Figure 17. Demonstrator 2 concept.

Patient identification is also essential in medical environments to ensure the correct treatment or surgery. This is particularly relevant in critical treatments such as radiology or chemotherapy, where the wrong dose may lead to harmful or even irreparable effects on patients. In some cases, patients must undergo certain diagnostic tests such as magnetic resonance imaging (MRI) scans, which are incompatible with devices that transmit information via radiofrequency waves. These situations require some kind of robust identification in these environments. Hospitals typically employ sensitive systems that can be interfered by some equipment. Particularly, devices using radio signals, e.g., mobile phones, could interfere with common hospital equipment such as sensitive measurement, analysis and monitoring equipment. At the same time, radio is still very important to ensure communication in situations where VLC is not available, e.g., at rehabilitation or during a walk outdoors.

In large-scale medical environments, providing connectivity to patients, medical and support staff, alarm/energy systems, and equipment is of substantial importance. Patients should have sensors measuring their vital signs and communicate this data to a gateway. Patients should be accurately located and should be able to send alarm messages when needed with high quality-of-service to nurses. In general, patients will require connectivity in both directions. Thus, sensor measurements, for instance, need to be transmitted to the network for further processing, and conversely, control information could be sent to actuators or other functionalities at the tag/label. Moreover, important equipment and medical devices should also be connected in order to ensure timely reporting, and their location should be easily tracked. Alarming systems are critical in medical institutions, which do not only cover patient emergencies but also other emergencies, e.g., fire. Such alarm system should have high quality of service (QoS) to ensure timely reporting and actions.

Table 33 summarizes the potential SUPERIOT applications identified for demonstrator 2.

Table 35. Selected potential applications for demonstrator 2 (subset of Table 25).

Demonstrator	Potential Application
#2	1.3 – Tags and labels specifically designed for medicines
	1.4 – Tags specifically designed for logistic operations
	1.7 – Tags and labels for healthcare patients
	1.9 – Labels for tracking critical equipment
	2.3 – Sensors for medical and safety applications
	3.1 – Secure and private IoT communication
	3.2 – Reliable IoT communication

The potential applications of the first scenario (1.x) are derived from the idea of future smart tags and labels for identification and traceability of objects (static or moving) and people, with enhanced functionality. Some of these applications are currently accomplished with existing technology, such as QR codes, RAIN RFID, NFC, etc. Some of these technologies are nowadays used in medical ICT scenarios, however, they lack some of the characteristics to be able to be deployed in a large-scale, namely their cost and sustainability. SUPERIOT addresses some of the missing characteristics and together with the remaining (dual-mode communication, localization capabilities, etc.) could really change the way medical processes work today.

Applications of scenario 2 (2.x) are linked to the idea of sustainable and inexpensive devices that can be deployed in large scale for environment sensing and actuation. This idea of large-scale sensing and actuation is a trending topic for LPWAN technologies. Self-deployable networks like LoRaWAN or networks available from communication operators like NB-IoT and SigFox are already enabling large-scale sensing and actuation. In medical scenarios, the need for monitoring and controlling the environment is very important and the current technologies are in many ways far from the SUPERIOT vision.

Finally, applications from scenario 3 (3.x) may be seen as enhancements for IoT communication in general. In this sense, these topics may be seen as improvements to the current technologies being used in the different applications.

6.4.2 Existing solutions and SUPERIOT opportunities

As mentioned above, there are already existing technologies to address some of the medical ICT challenges. Table 34 summarizes the different existing technologies for each application.

Table 36. Existing solutions for each application of demonstrator 2.

Potential Application	Technology of Existing Solutions
1.3 – Tags and labels specifically designed for medicines	Barcode/QR code; HF RFID (NFC) labels; UHF RFID (RAIN RFID) labels.
1.4 – Tags specifically designed for logistic operations	HF RFID (NFC) labels; UHF RFID (RAIN RFID); LPWAN tags, e.g., using NB-IoT, LoRa, and/or Sigfox
1.7 – Tags and labels for healthcare patients	Tyvek bracelets with barcode/QR code; A unique BLE tag assigned to each patient
1.9 – Labels for tracking critical equipment	HF RFID (NFC) labels; UHF RFID (RAIN RFID); BLE tags used to track equipment and locate them in room basis

2.3 – Sensors for medical and safety applications	BLE/BLE mesh bracelets for patients' vital sign mounting and tracking within hospitals/care centers.
3.1 – Secure and private IoT communication	RFID for patient tracking and medication management, NB-IoT for connecting medical sensors and devices to the network, Barcode/QR bracelets
3.2 – Reliable IoT communication	QoS implementation in BLE/BLE mesh

Similarly to the applications of demonstrator 1, there is a set of technologies that is commonly used to address most of the applications, namely:

- Optical readings (barcode/QR code)
- HF RFID (NFC) labels
- UHF RFID (RAIN RFID) labels
- BLE bracelets
- LPWAN tags, sensors and actuators (LoRaWAN, NB-IoT, SigFox)

Using the technology comparison table (Table 29), and taking into account the medical scenarios, there are some opportunities for SUPERIOT technology.

Based on this analysis, there are already solutions with interesting functionalities, such as sensing and actuating capabilities, reconfigurability and location. However, the same problem exists: most of these capabilities come with the need of a conventional recharging or one-use battery. This poses an immediate pricing problem, but also leads to high recurring maintenance costs and environmental unsustainability. These are some of the reasons, why even though medical scenarios are critical, and their challenges are a priority when it comes to technology developments, there are still no technological solutions similar to SUPERIOT largely deployed.

Most of the solutions deployed are those that do not need conventional batteries (optical and passive RFID labels), and they are not capable of providing the necessary communication, monitoring and location that these challenging scenarios require today.

For this reason, there is an interesting opportunity for SUPERIOT to demonstrate an autonomous and reusable solution that can provide more functionality than the most common autonomous solutions provide today.

Another relevant topic in medical scenarios is the challenges of radio communication when there are electromagnetic (EM) interferences. This occurs frequently in medical scenarios since there are machines like MRI, X-Ray, etc. that create strong EM environments. The dual-mode communication and reconfigurability of SUPERIOT technology can help create a robust solution for operating and transmitting data in these EM challenging environments.

Although EM challenging environments are seen as a constraint, they can also be seen as an opportunity for SUPERIOT. Since the proposed technology is trying to use energy harvesting from existing sources, these EM fields (e.g., MRI) may be used to help the gathering of energy for the operation of the nodes.

6.4.3 Types of environments

As previously mentioned, the type of environment where each application is applied plays an important role when defining requirements. In the case of demonstrator 2, the applications focus medical ICT scenarios. In that sense, even though some of the applications identified may have a broader applicability, the environments that are relevant to this specific demonstrator are those that have a connection to medical ICT scenarios (hospitals, care centers, etc.). Table 37 identifies the most important types of environments and Table 38 their most relevant characteristics.

Table 37. Types of common environments of each potential application of demonstrator 2.

Potential Application	Types of Environments
1.3 – Tags and labels specifically designed for medicines	Hospital; Pharmacy; Warehouse; Outdoor Transportation.
1.4 – Tags specifically designed for logistic operations	Hospital; Pharmacy; Warehouse; Outdoor Transportation.
1.7 – Tags and labels for healthcare patients	Hospitals; Primary Care Centers; Home.
1.9 – Labels for tracking critical equipment	Hospitals; Warehouse; Outdoor Transportation.
2.3 – Sensors for medical and safety applications	Hospitals; Primary Care Centers.

Table 38. Relevant characteristics of the most common environments of demonstrator 2 applications.

Types of Environments	Radio communication coverage area	Energy Harvesting sources	AP deployment height	AP deployment density
Hospital	Varied indoor spaces (patient rooms, hallways, operating rooms) Network: LAN for critical areas and WAN for hospital-wide coverage to connect various departments and buildings.	Solar energy, ambient light, energy from other nodes	Ceiling height (approx. 3m)	Medium to high density, particularly in critical care areas.
Pharmacy	Medium sized indoor spaces. Reliable coverage required for tracking medical inventory. Network: LAN	Solar energy, ambient light, energy from other nodes	Ceiling height (approx. 3m)	Low density
Primary Care Centers	Network: LAN WAN to relay patient information between primary care centers and hospitals	Solar energy, ambient light, energy from other nodes	Ceiling height (approx. 3m)	Medium to high density
Home	Network: LAN WAN for real-time remote patient monitoring	Solar energy, ambient light, energy from other nodes	Ceiling height (approx. 3m)	Low density
Outdoors	Open outdoor areas with potential obstructions like trees, buildings, etc. Network: WAN	Solar energy	Deploy Aps on tall structures like poles, buildings	High density for wide coverage
Warehouse	Large indoor spaces. Comprehensive and reliable coverage is essential for inventory management and logistics. LAN within the warehouse, and potentially WAN for communication with other facilities or logistic networks.	Solar energy, ambient light, energy from other nodes	Ceiling height (approx. 10m)	High deployment density

6.4.4 Selection of the most relevant applications for Demonstrator 2

In this section, a further selection of the most relevant applications is performed for Demonstrator 2, taking into account the project's objectives and concept, but also regarding the specific demonstrator goals.

Demonstrator 2 aims to use a network that will create a real-time spatial map of resources and their current status such as a) availability, current usage as well as location of equipment and objects, b) health monitoring, current needs and general requirements of patients, c) availability, skills, location and current degree of working load of medical personnel. In addition, physical access to rooms can be provided by the same system.

For that reason, applications that focus on patients, medical equipment and hospital personnel are the most interesting candidates for Demonstrator 2. Besides that, the applications that deal with mobility of equipment, personnel and patients are particularly interesting for the project concept.

Based on these points the following applications were selected as the most relevant for Demonstrator 2.

Table 39. Most relevant applications for demonstrator 2.

Demonstrator	Potential Application
#2	1.7 – Tags and labels for healthcare patients
	1.9 – Labels for tracking critical equipment
	2.3 – Sensors for medical and safety applications

6.4.5 Use cases and functional requirements

In this section, one example of use cases is described, and the corresponding functional requirements are derived. As mentioned before for demonstrator 1, the use cases specified are not meant to be necessarily the use cases to be demonstrated in the project, they are just examples to help define ranges of values for the requirements that can be seen as guidance for the development of SUPERIOT technology.

6.4.5.1 Use case example 3: patient monitoring

Overview

Emergency rooms (ERs) are specialized units within hospitals and healthcare facilities that provide immediate medical care to patients who are experiencing acute illnesses, injuries, or other medical emergencies. ERs play a crucial role in the healthcare system, as they are often the first point of contact for individuals seeking urgent medical attention.

There are many challenges that make emergency rooms one of the most important beneficiaries of technological innovations. The most important one is the criticality of fast medical care in most situations. However, there are other challenges that amplify the need for better tools.

Effective managing the flow of patients through the ER is essential to prevent bottlenecks and ensure prompt care. This makes the communication among healthcare providers critical. Handoffs between shifts or departments must be well-coordinated to avoid errors in patient care.

These are by themselves complex challenges, and ERs have well-defined processes to try to overcome them. But the problem is even intensified with the common situations of overcrowding. Overcrowding is one of the most common emergency room problems. High patient volumes can lead to extended wait times, delayed care, and increased stress on staff and resources.

When patients are waiting inside the emergency room, they are typically not being monitored, i.e., their vital signs or other relevant parameters are only monitored in some situations, normally when patients are already hospitalized. This means that if a triage process is not effective or if the clinical situation of the patient degrades quickly, there is no way to realize it. Even when the clinical situation of patients is stable, the need to direct patients between different departments, e.g., to perform exams, pose efficiency problems when managed with manual processes.

All this complexity can result in process errors and ultimately lead to patient death.

Nowadays, when a patient enters an emergency room, he goes through a triage process (e.g., Manchester Triage Process) and he is assigned a level of medical care priority. This is normally reflected on the color of a bracelet that also contains his identification. There are already some experiments done where this disposable bracelet contains some improved technology, such as passive or active RFID tags. The first option is very interesting, since there is already a possibility of incorporating the technology in a disposable bracelet. However, passive RFID is not able to provide the reliability of communication needed for such a critical use case. Active RFID tags are a more reliable option, however, due to the cost of these tags this is only viable with reusage of bracelets, which is not possible in most cases. Even if this is tried, replacements of batteries and the amount of waste would not be sustainable.

In this sense SUPERIOT could really be game changing, with a solution that could be incorporated for example in the triage bracelet, but still with the necessary communication reliability that such use case needs. This reliability can even be particularly enhanced in SUPERIOT with the dual-mode (light/radio) communication. Critical information could be communicated at the same time on both radio and optical links. Moreover, light communication can be used in situations where they are strong electromagnetic fields that interfere with radio communication (e.g., MRI). By adding printed electronics sensors to this solution, the patient could be constantly monitored and traced inside the emergency room, strongly reducing potential medical errors, and saving lives.

Finally, even though patients in emergency rooms would be a natural first client of SUPERIOT, the same solution could be applied to other care centers, or even patients recovering at home. The opportunities are endless.

Description

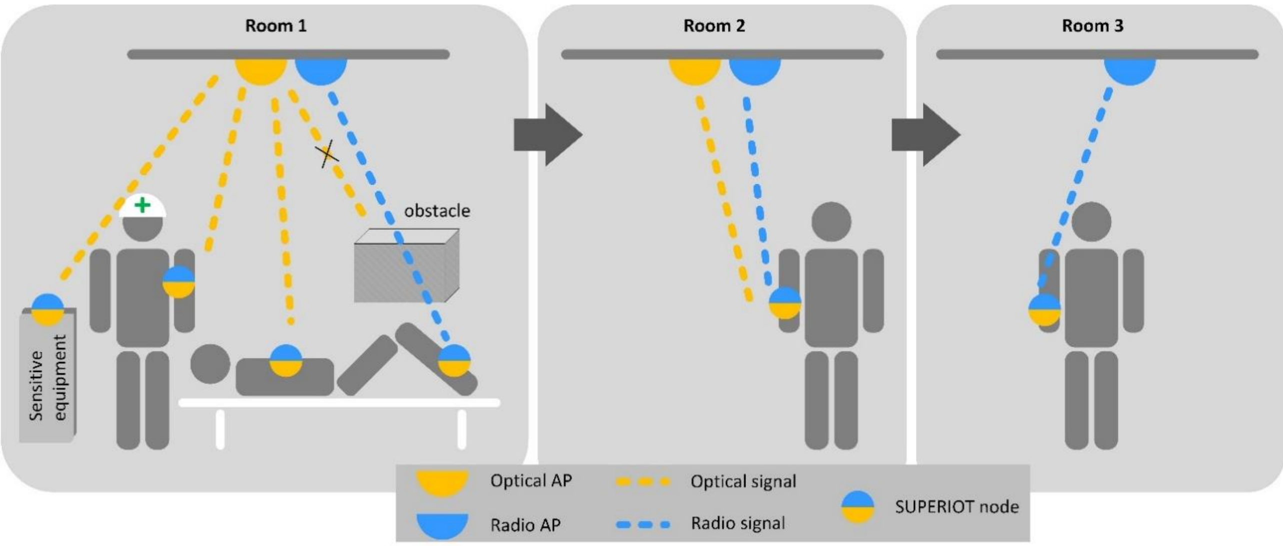


Figure 18. Example of using SUPERIOT concept in a hospital.

We describe next an example of how the capabilities of the SUPERIOT concept can be exploited. We consider the case of a patient going sequentially through different medical care in different hospital scenarios, exemplified by Room 1-3 in Figure 18. We assume that the patient enters an emergency room (Room 1) where his condition is assessed. Medical staff in the room attach to the patient active tags and labels. These devices can be stand-alone IoT nodes, with many different functions, for instance, monitoring vital physiological parameters, identifying the patient, etc. Moreover, these devices can be nodes of a WBAN carrying out complex monitoring and actuation functions on the patient. The emergency room may contain several sensitive instruments needed in the patient triage. In such case, the nodes (denoted as SUPERIOT nodes in the figure) can be configured to maximize the use of light signals for connectivity and localization purposes, as shown in Figure 18 (left). This will minimize possible interference problems with the equipment. If the light path between the optical access point and a node is obstructed or blocked by an object or person, the connection to that node could be replaced by the radio connection that is not affected by blockage. The wireless link could be reconfigured back to optical once the system detects that the physical obstruction has been cleared, for instance, due to mobility. Another reason to prefer the use of optical links could be security and privacy. If security level needs to be increased or hospital policy usage in that room demands strict security, the use of optical links for connectivity and localization will be favored. Then, the patient is moved to another room (Room 2) to undergo certain medical procedures, such an operation. In this case, the patient needs to be reliably connected to remote monitoring and actuation. For instance, based on vital signs being monitored, control signals will be transmitted in return, to control the operation of certain devices actuating on the patient, such as medicine dosifiers, etc. It is clear that the operation of such a critical control needs to be errorless. Dependable operation is fundamental in many medical ICT, and in our case, the SUPERIOT concept allows reconfiguration to achieve reliable communications. Figure 18 (center) illustrated this case, there the communication system is configured to use simultaneously both radio and optical links. The same critical signal is transmitted on both optical and radio channels, and signals are properly combined at the receiver, using well known principles of diversity. Note that the concurrent use of both radio and optical signals can be used for other purposes as well, for example to increase data throughput by transmitting different signals on different links, and to have a more robust and precise localization. The two cases find also use in healthcare environments. The patient may need to be moved to another hospital room for further treatment, Room 3 in Figure 18 (right) In this room, the patient may need to rest, for which, lights are turned off or dimmed. The system could be then configured to rely only on radio signals. A related situation may occur when the patient moves to an area where only one type of access point is available. This is the case, for instance, if the patient moves to an outdoor area in the hospital. He could be connected/monitored using radio links as shown in the figure.

This example highlights the flexibility and adaptability of the SUPERIOT concept, in particular for medical ICT scenarios. Demonstrator 2 will be based on the use of a network of reconfigurable IoT nodes attached to patients, medical personnel, equipment and objects of a hospital. Services exploiting connectivity and localization will be provided with an advanced network able to adapt to the changing requirements of the service, environment, service/network provider and others.

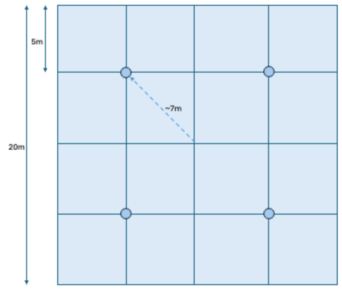
Functional requirements

To help define the functional requirements for this use case, available reference values for medical ICT sensors were used (Appendix 4), together with the experience of industrial partners in similar use cases.

Table 40. Functional requirements derived for use case example 3: patient monitoring in emergency rooms.

Requirement	Expected value (Range)	Comment
Data rate in DL	Min: 125 kbps Max: 1 Mbps	BLE VLC DL communication will be mostly related with reconfiguration and some possible simple actuation on the label. For this reason, the expected data rates are low (125 kbps). However, to accommodate for future possibilities of more complex actuation scenarios, data rates up to 1 Mbps should be considered.
Data rate in UL	Min: 125 kbps	BLE

	Max: 1 Mbps	RF Depending on the amount of sensing information to send, the data rate for UL will vary. Preferably, the data rate would be kept closer to the minimum value (125 kbps), in order to increase the lifetime of the label. However, depending on the health monitoring type performed to the patient, data rates may increase to values around 1 Mbps.
Frequency of signaling in DL	Min: 1 msg/min Max: 1 msg/sec	How often the node needs to be connected (e.g., every x min, continuously, etc.)
Frequency of signaling in UL	Min: 1 msg/min Max: 1 msg/sec	How often the node needs to be connected
Reliability	99	
Latency requirements	QoS implementation is needed Min: 1 us Max: few seconds	
Simultaneous operation of UL and DL	No	
Importance of dynamic reconfiguration	High	E.g., need for changing communication modes during operation
IoT node density	Up to 1 per sqm	Typically, there will be a density lower than one patient per sqm, particularly if patients are in hospital beds. However, in specially crowded situations, we expect that there may be up to 1 (standing) patient per sqm.
Mobility of nodes/objects	Yes	
Wireless range	Up to 4 meters	Hospital ceiling height is approx. 3 m
Node autonomy	Yes	Required operating time without energy harvesting
Expected localization accuracy in range	Less than 50 cm	BLE and VLC
Expected localization accuracy in angle	5 degrees	Depends on number of antennas
Expected localization accuracy in position	Less than 30 cm	BLE and VLC
Localization update rate	1 per 1 seconds	
Density of APs	4 APs per 400 square meters	In localization topics, APs are sometimes referred to as localization anchors. Since this scenario requires only room-based location information, only 4 APs are sufficient. Moreover, the number of RIoT nodes in example 3 is limited compared to other examples considered. The light intensity in patients rooms is rather high (> 700 lux), hence 4 APs are sufficient for communication and energy transfer. The number of horizontal distances can be relaxed to 7 m in hospital rooms for patient monitoring, thanks to the relatively high ambient light per unit (> 700 lux) in

		hospital rooms and the room-bounded communication range for both optical and RF.  Moreover, the number of RIoT nodes in example 3 is limited compared to other examples considered, hence 4 APs are sufficient for communication and energy transfer.
Expected average level of illumination in the environment (Lux) required by the node to operate	Min: 200 lux Max: 500 lux	
Sensors on board **Always on?**	Yes	
Actuators on board **Always on?**	Yes	
Data processing on node	Yes	
Modes of operation (as supported by SoC)	Active mode Idle/standby mode Sleep mode	
Radio transmission power	-20 dBm to +8 dBm	
Energy/Power consumption and storage requirements	Case 1 (1 second cycle): Average node's current consumption = 5 mA, Energy = 0.04 J/cycle Minimum supercapacitor size to sustain active operations in one cycle= 6 mF. Case 1 (1 min cycle): Average node's current consumption = 2.4 mA, Energy = 0.5 J/cycle Minimum supercapacitor size to sustain active operations in one cycle = 6 mF.	Case 1: All node functionalities enabled (BLE, NBVLC, Sensing, E-ink) in an operation cycle. The node does not sleep at any point in time during its operation cycle. It remains connected to a central device (e.g. gateway) throughout its whole operating period (considering a maximum BLE TX power level). The supercapacitor charges during idle period in the operation cycle. Case 2: Node's operations include startup state (due to wake-up), sensing and E-ink displaying, and deep sleep in one cycle, which is repeated every 1 second or 1 min (VLC and BLE

	Case 2 (1 second cycle): Average node's current consumption = 7 mA, Energy = 0.1 J/cycle Minimum supercapacitor size to sustain active operations in one cycle = 14 mF. Case 2 (1 min cycle): Average node's current consumption = 0.3 mA, Energy = 0.06 J/cycle Minimum supercapacitor size to sustain active operations in one cycle = 14 mF.	both off). the supercapacitor charges during deep sleep period in the operation cycle.
Scalability	250 million labels per year, and coverage of hospital's emergency department	In Europe, Emergency Department visits rank from 100-300 visits per 1000 habitants per year[1]. European population is close to 750M, which leads to 225 million visits per year (considering the 300 visits per 1000 habitants). [1]https://eusem.org/images/European_EM_in_numbers.pdf

6.5 Demonstrator 3 – Printed Limited-capability IoT Node

6.5.1 Demonstrator overview

Demonstrator 3 is designed as a fully printed, rather simple IoT node with limited capabilities. It will be developed with the aim of demonstrating the feasibility of the SUPERIOT concept in terms of a truly sustainable implementation (Figure 20).

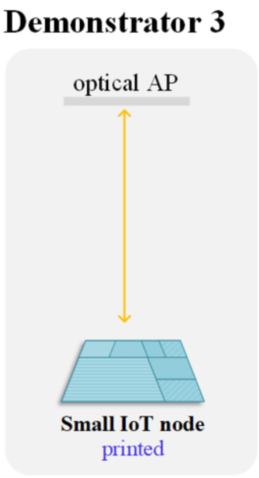


Figure 19. Demonstrator 3 Concept.

The targeted limited-capability node will be energy-autonomous, and capable of receiving and transmitting/displaying some information (e.g., alphanumeric characters and icons). Therefore, the developed IoT nodes are expected to be a crucial component for smart labels and tags attached/incorporated in conventional products or sensitive items and sensors/actuators for smart buildings. These would not only replace conventional labels, such as barcodes and RFIDs, but could also monitor and even actuate inside buildings. These units, along with other possible on-board functionalities, will be simplified to a bare minimum to match the capabilities of current printed electronics technology - hence, the work will be mostly carried out in the analogue electronics domain. The design of the node will therefore be radically different from the design of conventional IoT nodes. In summary, the aim for this demonstrator is to (i) create a benchmark of capabilities of the current state of the art printed electronics in a functional IoT device and (ii) demonstrate that SUPERIOT concepts can be exemplified in these IoT devices with extremely limited capabilities, opening up the possibility for the future to have sustainability, low-cost manufacturing, radio RF/VLC communication and localization, and energy harvesting using only printed electronics.

For Demonstrator 3, the previously described potential future applications are shown in Table 41.

Table 41. Selected potential applications for demonstrator 3 (subset of Table 25).

Demonstrator	Potential Application
#3	1.1 - Smart labels attached or incorporated in day-to-day market products (with reduced capabilities)
	1.2 - Smart tags incorporated in sensitive items (with reduced capabilities)
	2.1 - Sensors and actuators for smart buildings (with reduced capabilities)

As previously described, the first scenario applications 1.1 and 1.2 involve advanced smart tags and labels for identifying and monitoring objects. These outperform traditional codes like barcodes, QR, and passive RFID. These smart tags go beyond tracking, by including tailored sensing and actuation for assigned objects. By using printed tags with unique identifiers embedded directly into sensitive items during manufacturing, like in-mold electronics, the risk of item counterfeiting and the associated problems for manufacturers, retailers, and end customers can be mitigated. They connect to a network, connecting the objects as IoT nodes, aligning with SUPERIOT principles: printed electronics, cost-effective production, RF/VLC communication, localization, energy harvesting, and sustainability. These applications and the described requirements expectations are currently a very big challenge for a fully-printed node, however, they can be used as a reference and the guidance for future development.

Application of scenario 2.1 is related to sustainable IoT devices for large-scale building monitoring and actuation. This can detect environmental conditions, such as light intensity, temperature, and humidity, monitor electrical consumption, and perform actuation as a response to certain event/data thresholds. Deploying more nodes increases monitoring capabilities. Printed electronics can help reduce the cost and help the large-scale deployment, while VLC/RF communication bolster security, privacy in wireless access control systems, and reduce battery waste through energy scavenging strategies. Building safety could improve via light-defined safety zones, and communication with sensors e.g., in smart workwear. Incorporating smart certificates in equipment enables alerts when certificates are running out or auto shutdown when depleted. Again, these applications are far beyond the scope of the fully-printed node that will be developed in SUPERIOT project, but they help understand what could be expected in the future.

6.5.2 Existing solutions and SUPERIOT opportunities

Table 42 provides an overview of the most common technologies used in conventional existing solutions for each application, which can be helpful for identifying the most interesting SUPERIOT opportunities for the fully-printed node in the future.

Table 42. Existing solutions for each application of demonstrator 3.

Potential Application	Technology of Existing Solutions
1.1 - Smart labels attached or incorporated in day-to-day market products (with reduced capabilities)	HF RFID (NFC) labels; UHF RFID (RAIN RFID) labels.

1.2 - Smart tags incorporated in sensitive items (with reduced capabilities)	HF RFID (NFC) labels; UHF RFID (RAIN RFID) labels.
2.1 - Sensors and actuators for smart buildings (with reduced capabilities)	Sensors with different communication technologies: Wi-Fi; BLE; ZigBee; LoRaWAN; NB-IoT.

As described for the previous demonstrators, most of the existing solutions for demonstrator 3 use a limited set of communication technologies, such as:

- HF RFID (NFC) labels
- UHF RFID (RAIN RFID) labels
- Wi-Fi tags, sensors and actuators
- WPAN tags, sensors and actuators (BLE, ZigBee, UWB)
- LPWAN tags, sensors and actuators (LoRaWAN, NB-IoT, SigFox)

The qualitative comparison table (Table 29) describes the different features of these currently available solutions. HF and UHF RFID labels are able to operate without batteries, but since they have Si-based microcontrollers, their cost is not negligible and their usage in large-scale has sustainability issues. Their functionalities are also limited, they work with magnetic coupling or backscatter, so they only operate when close to readers and they are not normally equipped with sensing or actuating capabilities.

Wi-Fi, WPAN and LPWAN have more functionalities and are closer to a truly smart tag. However, these options are not sustainable since they are either based on single-use or recharging batteries. Moreover, they do not feature printed electronics technologies, which make them quite expensive to be massively deployed.

When compared to battery-powered solutions, the number of available functionalities is expected to be significantly reduced when it comes to battery-free, fully-printed solutions, at least in its initial approach. But their potential low cost, sensing and actuating capabilities, can make them an interesting alternative, even with some interesting improvements in functionality when compared with HF and UHF RFID labels.

The SUPERIOT project aims to develop a prototype that can exemplify some of the functionalities of a fully-printed node of the future and show that in some applications one could benefit from widely deposited, more sustainable, and lower cost nodes with simpler functionality. These functionalities are currently limited by the variety and performance of printed electronic devices (sensors, actuators, displays, logic, and communication circuits).

In comparison to the other demonstrators, more complex functionalities will have to be discarded. By removing Si-based electronics, signal processing, and communication will be based on analog methods, which tend to be less complex and power-consuming than their digital counterparts. Notably, the nodes will have limited capability of providing unique identifiers as with the conventional Si-based digital technologies. The tags cannot comply to current communication standards (e.g., IEEE 802.11 or Bluetooth) due to the absence of digital technologies, which leads to both minimal communication rates and absence of e.g., Bluetooth-based localization.

Similarly, reconfigurable operation or dual-mode operation in general cannot be obtained without Si-based microcontroller units (MCUs). In addition, the variability between nodes can be considerable due to substantial device-to-device variation among the printed devices.

The node will not have energy management capability due to the absence of Si-based PMUs and, thus, will operate when energy is supplied to the node. For example, in the case organic photovoltaics (OPVs) are used for energy harvesting, this can mean that the node operates only when it is subjected to light and similarly for RF energy harvesting. The node is likely to be operated only in indoors conditions, unless very robust encapsulation is used to allow withstanding harsh outdoor environmental conditions (e.g., heat and high humidity), which is beyond the scope of the SUPERIOT project. Also, the lifetime of the node can be limited when compared to Demonstrator 1 and 2 as the long-term stability of printed electronics is inferior to conventional Si-based electronics. In some cases, this is not necessarily a hindsight as using stabile less-sustainable Si-based electronics for short life-time and single-use nodes is an exaggerated solution.

As a summary, the Demonstrator 3 is likely to have a simpler configuration than Demonstrators 1 or 2, but still, it should operate by energy harvesting, provide some sensing function, and communicate either via light or RF, although the communication frequency might not be a standard communication frequency due to the limitations of printed components in RF operation (especially above MHz). The potential for utilizing sustainable materials in the node construction can offer simpler end-of-life strategies (e.g., recycling, biodegrading or composting) than those nodes with Si-based electronics. The potential for low-cost fabrication through cost-efficient high-throughput printing methods (e.g., roll-to-roll printing) offer an opportunity for fully-printed nodes in applications where Si-based or hybrid nodes would be of too high cost.

As a conclusion, these two opportunities suggest an application niche where single-use and wide deployment (e.g., price-sticker-like) are limiting Si-based options through too high cost per unit and/or difficulty of end-of-life treatment (e.g., non-compliance with paper recycling streams). Demonstrator 3 is meant to be fully-printed, autonomous, and sustainable showcasing the tremendous potential of fully-printed technologies in low-cost and sustainable nodes.

6.5.3 Types of environments

The type of environment where each application is applied is very important to understand the constraints that the deployment of fully-printed nodes will encounter in the future. For this purpose, the list of candidate applications was mapped to the most common types of environments where they could be used.

Considering the potential applications proposed for demonstrator 3 a set of environments can be proposed as shown on Table 40.

Table 43. Types of common environments of potential applications of demonstrator 3.

Potential Application	Types of Environments
1.1 – Smart labels attached or incorporated in day-to-day market products (with reduced capabilities)	Supermarket; Warehouse; Outdoor transportation.
1.2 – Smart tags incorporated in sensitive items	Store; Supermarket; Outdoor transportation.
2.1 - Sensors and actuators for smart buildings	Office; Hospital.

In turn, the defined environments will exhibit characteristics as described in Table 44.

As previously mentioned, outdoors scenarios would pose challenges beyond the scope of SUPERIOT for the fully-printed node. For that reason, its analysis was not considered.

Table 44. Relevant characteristics of the most common environments of demonstrator 3 applications.

Types of environment	Communication coverage area	Energy harvesting sources	AP deployment height	AP deployment density
Hospital	LAN	Multi light sources	3 m height	High density
Office	Small LAN	A single light source	3 m height	Low density
Store	Small LAN	Multi light sources	3 m height	Medium density

Supermarket	Small LAN	Multi light sources	3-5 m height	Medium density
Warehouse	LAN	Multi light sources	10 m height	Medium density

6.5.4 Selection of the most relevant applications for Demonstrator 3

Demonstrator 3 aims to demonstrate the operation of a fully-printed limited-capability IoT node. This node will be energy-autonomous, and capable of receiving and transmitting/displaying some information (e.g., alphanumeric characters and icons). Rather than demonstrating the advanced capabilities of the SUPERIOT concept, Demonstrator 3 aims at showing the potential of printed electronics technology as a key implementation technology for IoT devices. As this technology advances, we expect that in the future sophisticated IoT nodes such as the ones developed for Demonstrators 2 and 3 will be fully printed, paving the way to a myriad of novel applications with sustainable implementations.

Even though this concept can be applied to the different mentioned applications, the capability of displaying information in a fully-printed node makes this technology particularly interesting for future smart labels attached or incorporated in day-to-day market products. These labels would work as stickers, making it possible to monitor the quality of the products as well as display relevant product information in real-time. Modification of prices or expiry dates, based on the environment or other conditions that affect the product could also be implemented. Product recall information could also be diligently transmitted and displayed only on the affected products This would help increase consumers' safety and experience by having this information .updated in the printable display. Accurate localization would help in handling procedures, both in stores and logistics.

For this reason, this application is selected as the most relevant to be demonstrated in Demonstrator 3, even considering that it will be developed with reduced capabilities.

Table 45. Most relevant applications for demonstrator 3.

Demonstrator	**Relevant Application**
#3	1.1 - Smart labels attached or incorporated in day-to-day market products (with reduced capabilities)

6.5.5 User requirements

As mentioned in the beginning of Section 6.1, demonstrator 3 will not be developed based on specific end user applications, but rather driven by the technology developed during the project. In that sense, it is not possible to define, at this point, functional requirements for the fully-printed node. However, to ensure that partners have a common understanding of the desired fully-printed node, some expected high-level requirements were defined. Table 46 summarizes these requirements.

Table 46. Expected requirements for the fully-printed node.

Potential Application	**Types of Environments**
Reliability in different operational environments (dual-mode communication)	Capability of communicating over light or radio (no dual-mode is possible without Si-based MCU)
Security and privacy (dual-mode communication)	Since dual-mode communication is not available, enhancements of security and privacy will not be a focus of the fully-printed node
Price (cost efficient manufacturing)	Cents of euros or even less with mass production

Position accuracy	Mainly presence and movement detection, but possibility of having location by increasing the complexity of the infrastructure
Sensing capabilities	Possibility of measuring sensor values once per hour, or even more frequently.
Actuating capabilities (namely display)	Possibility of changing a simple display or visual indicator (organic light-emitting diode (OLED) or similar) once per hour, or even more frequently
Eco friendly	Sustainable, no conventional batteries, preferably needs to be recyclable, biodegradable or compostable
Autonomy	Autonomous (energy neutral)
Frequency of communication (energy consumption and energy harvesting)	Small number of communications per day, or even more frequently, depending on the energy balance and purpose
Reusable (printed electronics and sustainability)	Reusable and possibly reconfigurable
Recyclable/Disposable (printed electronics and sustainability)	Part of some recycling streams like paper or cardboard or bio-waste (biodegradable or composable). In worst-case scenario, disposable as household waste.

Regarding the sensing capabilities, the following analog sensing node mechanisms could be explored: (1) A sensor powered by light (through OPV) changes oscillation frequency of printed circuit that is changing the frequency optical uplink (e.g., OLED). (2) A sensor is connected to a tank circuit that changes the resonance frequency of the backscattered signal. (3) A sensor powered by light (through OPV) is connected to a printed analog circuit that changes indicator (simple segmented display) level with respect to sensor output level.

In terms of actuating capabilities, a printed seven-segment e-paper display can be considered for the simple content displaying on the fully-printed IoT node. It is an important element involved in energy consumption. The exemplary seven-segment E-paper display consists of one digit with dimensions of 9 mm per 23.6 mm. It is reported as consuming 0.73 mJ per refresh [24]. The double digits version consumes 1.56 mJ [25]. Similar 1.53 mJ consumption is reported for the seven-segment bar graph E-paper display [26]. All of these printed displays require a short refresh pulse every 2 minutes [24][25][26]. This short refresh pulse requirement can induce excessive energy consumption. It would be desirable to extend this period as much as possible or not apply it when it is not necessary.

To provide above-mentioned 0.73 mJ of energy only for the seven-segment display, assuming that the node operates discharging the capacitor(s) from 3.3 V to 1.8 V, omitting the low-dropout regulator (LDO) losses, there is needed 0.2 mF of capacitance per one digit refresh. The LDO (or another voltage converter) is needed due to the seven-segment display minimum and maximum voltages: 1.0 V and 1.55 V, respectively. Assuming LDO efficiency of 60%, it could be at least 0.33 mF of capacitance per one digit refresh. For the signed double-digit E-paper display (1.56 mJ consumption) and bar graph e-paper display (1.53 mJ consumption), assuming the same LDO efficiency, it could be ca. 0.7 mF.

6.6 Demonstrator 4 – Large-area IoT Node

6.6.1 Demonstrator overview

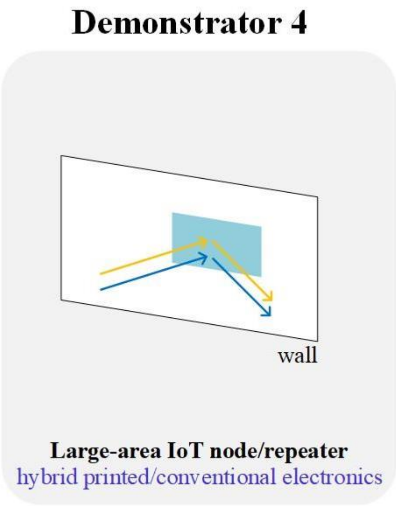


Figure 20. Demonstrator 4 concept.

The planned Demonstrator 4 will consist of a prototype implementation of a large-area IoT repeater/node that will demonstrate its capability of extending the communication range. This will be carried out by exploiting the concept of reconfigurable intelligent surface. Even though the large-area IoT repeater may be used in the future for different complex applications, the main focus of the project is to show that it is possible to use the large-area IoT repeaters to extend coverage, making application 3.5 (Coverage extension with large-area IoT nodes) the most relevant application to show in Demonstrator 4.

Demonstrator 4 will be based on 2 tasks:

1. Design of building blocks for large area IoT repeater/node
2. Integration and demonstration of large area IoT repeater/node

Task 1: Design of building blocks for large area IoT repeater/node

The first task involves designing building blocks for a large-area IoT signal repeater/node using reconfigurable intelligent surfaces with reflective antenna elements controlled by memristive or PIN diode-based switches. The task includes three main phases:

- Design of Test Fixtures:

  Initially, test fixtures based on microstrip transmission lines will be designed. These fixtures will facilitate the fabrication and characterization of reference memristor devices. Characterization will involve measuring S parameters in the microwave band and electrical properties (I-V curve) of different memristor devices.

- Antenna Element Design:

  After characterizing the memristor devices, the data will be used to identify candidate designs for antenna elements with tunable phase. These antenna elements will incorporate the memristor based switch devices and will be compared with PIN diode switches working as reference devices. Various designs, including conductive ink-based and copper-based versions, will be considered. The target frequency for these designs is 2.4 GHz, and they will be sent for fabrication and characterization.

- Array Optimization:

  The task will progress from a 1x5 array to a 5x5 array (approximate size of 30 x 30 cm). The array's geometry will be optimized in terms of the reflection coefficient, using experimental results from the measured phase shift characteristics of antenna unit cell elements. The fabricated antenna arrays will be characterized in an anechoic chamber, assessing parameters such as reflection coefficient bandwidth, gain, radiation efficiency, and static radiation patterns in both E and H planes. Target gains for the 1x5 and 5x5 arrays are expected to be around 12 and 19 dBi, respectively, with radiation efficiencies above 90%.

Task 2: Integration and demonstration of large area IoT repeater/node

This second task aims to integrate the 5x5 antenna array prototype developed in the previous task with an field programmable gate array (FPGA) prototype implementing a digital control algorithm. The goal is to experimentally evaluate beam scanning up to 60 degrees and validate it against simulation results, demonstrating the proof-of-concept functionality of a large-area IoT repeater/node. The breakdown of the second task is as follows:

- FPGA Implementation of Digital Control Algorithm:

  Properly wrap the code into a Python driver to easily control the RIS reflection. On the first phase, the task focuses on implementing the digital control algorithm on an FPGA. An algorithm for synthetizing coding patterns for single-beam steering will be designed in MATLAB, supporting a one-bit control scheme. A Linux based operating system allowing for the interface with the FPGA GPIO pins will be prepared. The coding pattern algorithm will then be properly wrapped into a Python driver to easily control the RIS reflection.

  Experimental validation will occur first in a standalone mode for functional verification and then in conjunction with one of the developed antenna unit cell elements to ensure proper control of the bias voltage at the antenna interface. An electronic interface will be developed to test the digital control algorithms with single antenna elements and the prototype antenna arrays.

- Integration of Antenna Array Prototype with Digital Control:

  In the second phase, the task focuses on integrating the fabricated antenna array prototype with the FPGA-based digital control system.

  Building on the results of previous task, where the antenna array was characterized in terms of static performance without digital control, the FPGA-based digital control system will be integrated with the reflect-array to experimentally validate beam-scanning functionality.

  Experimental characterization will involve sweeping a single pencil beam through digitally controlled reflection angles ranging from 0 to 60 degrees for normal incidence. It will also consider the maximum achievable steering angular range for different incident angles.

  The outcome of this task will be an FPGA-based prototype implementation of a digital control algorithm integrated with a 5x5 antenna array prototype. This integration will demonstrate the basic functionality of a large-area IoT repeater/node, particularly its ability to perform beam scanning for IoT signal enhancement.

6.6.2 Requirements and simulations

The central idea is to demonstrate beam steering using the 2.4 GHz RIS to reflect in an optimum manner Wi-Fi or BLE signals towards an IoT node (developed within demonstrator 1) that moves in front of the RIS; the position of this moving node must be known by the RIS controller to allow for configuring the beam to the correct angle. This position should be provided by the dual-mode localization platform developed in the project. This angle can also be inserted manually through the Phyton driver for testing. The moving node may report the received power as it moves (comparing the situation of RIS tracking on and off). Additional features that the demonstrator might provide:

- energy harvesting capabilities could be explored as part of this demo. The advantage of using the RIS tracking in charging the IoT node (from Demo 1) can be analyzed, potentially taking advantage of energy measurement capabilities of the node.
- calculation of RIS profiles with pattern nulls, that we could relate with a security feature.

6.6.2.1 *Link budget analysis*

The use case depicted in Figure 1 shows a general RIS-assisted single-input single-output (SISO) wireless communication system, with regularly arranged unit cells. Assuming that there is no line of sight (LoS) path between the transmitter antenna Tx and the receiver antenna Rx, the received signal comes mainly from the reflection of the RIS as follows. The transmitter emits a signal to the RIS with power P_t through an antenna with normalized power radiation pattern $F(\theta_t, \varphi_t)$ and antenna gain G_t. The signal is reflected by the RIS and received by the receiver with normalized power radiation pattern $F(\theta_r, \varphi_r)$ and antenna gain G_r. Here, d_1 and d_2 denote the distance between the transmitter and the center of the RIS, and the distance between the receiver and the center of the RIS, respectively.

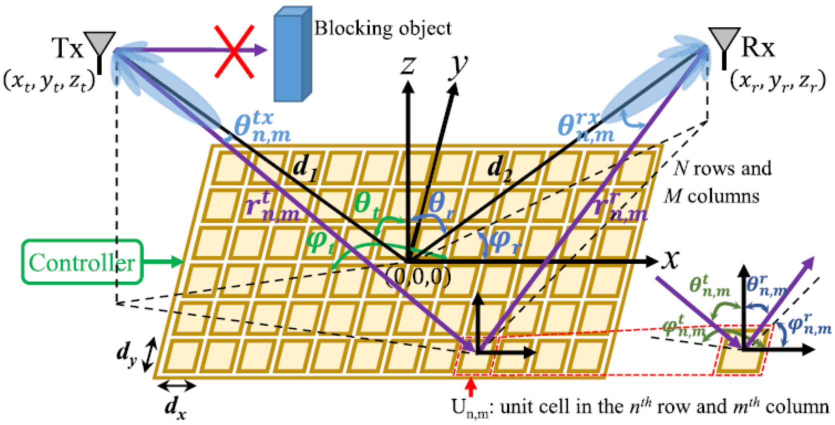


Figure 21. RIS-assisted wireless communication without the direct path between the transmitter and the receiver [27].

The received signal power in the far-field is given by [27]:

$$P_r = P_t \frac{G_t G_r G M^2 N^2 d_x d_y \lambda^2 F(\theta_t, \varphi_t) F(\theta_r, \varphi_r) A^2}{64\pi^3 d_1^2 d_2^2} \quad (1)$$

where G is the gain of the unit cell, M and N denote the number of columns and rows in the RIS, respectively, θ_t and φ_t represent the elevation angle and the azimuth angle from the center of the RIS to the transmitter, respectively, θ_r and φ_r the elevation angle and the azimuth angle from the center of the RIS to the receiver, respectively. The size of each unit cell along the x axis is d_x and that along the y axis is d_y, which usually is a fraction of the wavelength λ. The reflection coefficient A is assumed to be the same for all the unit cells [27].

Equation (1) assumes continuous phase shift at the RIS, which is an ideal phase shift model. The 1-bit discrete phase shift case leads to a penalty due to quantization loss, which is expected to be around 2-3 dB and 3-4 dB, for 10 × 10 and 40 × 40 unit cells, respectively, as depicted in Figure 2 [28]. Therefore, throughout this work we included a loss factor of 3 dB, to roughly take the quantization loss into account.

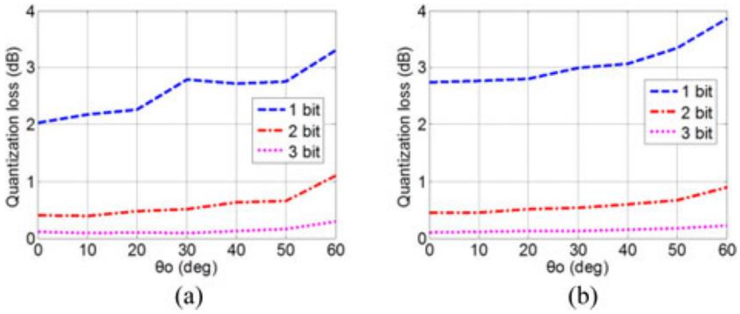


Figure 22. Quantization loss versus scan angle for different RIS size: (a) 10 × 10 elements and (b) 40 × 40 elements [28].

The link budget analysis was performed in MATLAB, using an algorithm based on the scenario described above. Thus, the received signal power was assessed using Equation (1), varying some parameters such as the receiver distance and the RIS size. Table 47 summarizes the parameters considered in the simulations. It was assumed that the RIS unit cell has a cosine radiation pattern, i.e., $F(\theta_t, \varphi_t) = \cos\theta_t$ and $F(\theta_r, \varphi_r) = \cos\theta_r$. For the sake of simplification, we considered square RIS only (i.e., $M = N$).

Table 47. Parameters for the simulation of RIS link budget.

Parameter	Description	Value
f	Frequency	2.4 GHz
BW	Bandwidth	1 MHz
$d_x = d_y$	Unit cell size	$\lambda/2$ (~6 cm)
G	Unit cell gain	5 dBi
A	Unit cell reflection coefficient	0.4
G_t	Transmitter antenna gain	10 dBi
P_t	Transmitter power	4 dBm
G_r	Receiver antenna gain	-10/0 dBi
NF_r	Receiver noise figure	7 dB

The signal-to-noise ratio (SNR) is calculated as follows:

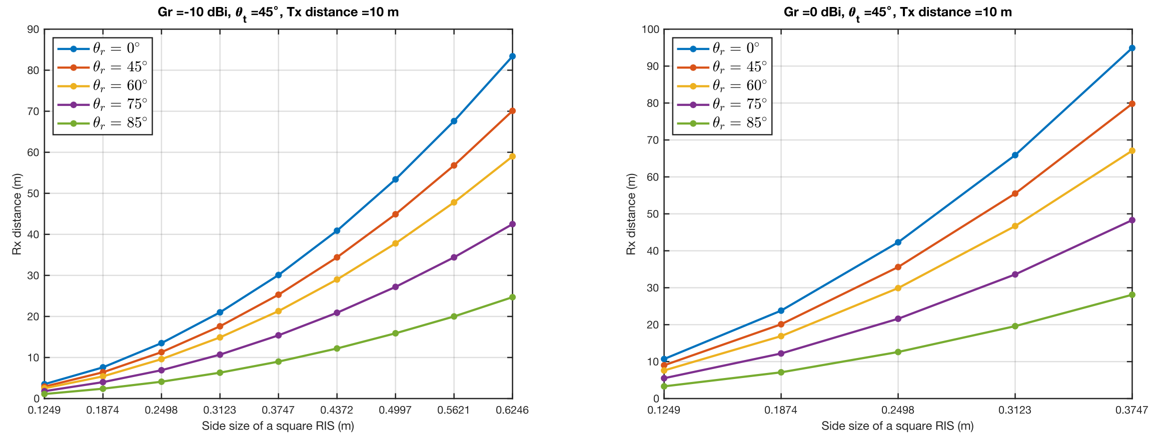
$$SNR_r = P_r - N_r - L_{quant}$$

where L_{quant} = 3 dB is the quantization loss and N_r is the received noise power given by:

$$N_r = -174 + 10\log_{10} BW + NF_r.$$

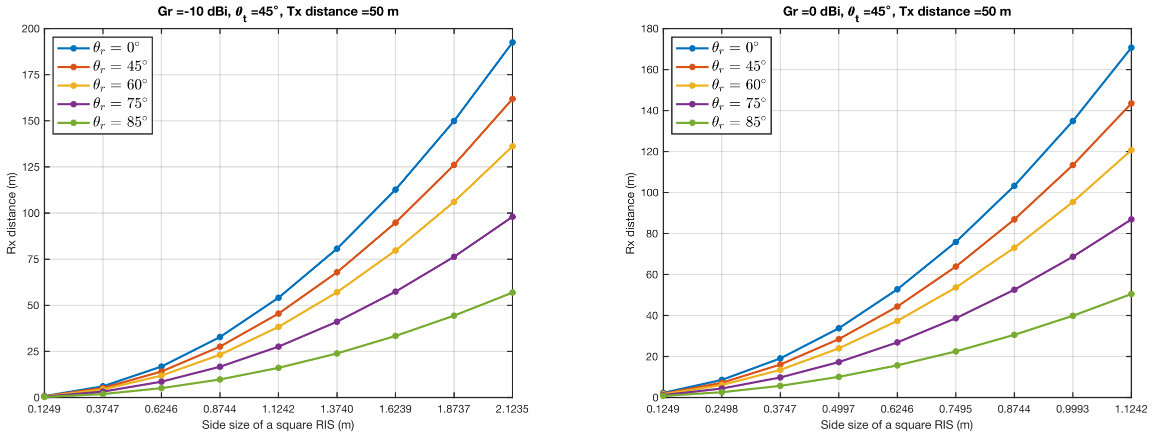
Firstly, we defined the target value for SNR of 10 dB, and obtained the distance between the receiver (i.e., user equipment) and the center of the RIS as a function of RIS size, depicted in Figure 23 (a) and (b), for a receiver antenna gain of G_r = -10 dBi and G_r = 0 dBi, respectively.

The distance between the transmitter and the center of the RIS is d_1= 10 m with an elevation angle of $\theta_t = 45°$. Also, different values of receiver elevation angle, θ_r, were considered, from 0° to 85° (i.e., from an ideal to a more deterring case), showing the performance degrading as the angle increases, as expected. This assessment was repeated for d_1=50 m and d_1=100 m, presented in Figure 24 and Figure 25, showing a similar outcome.



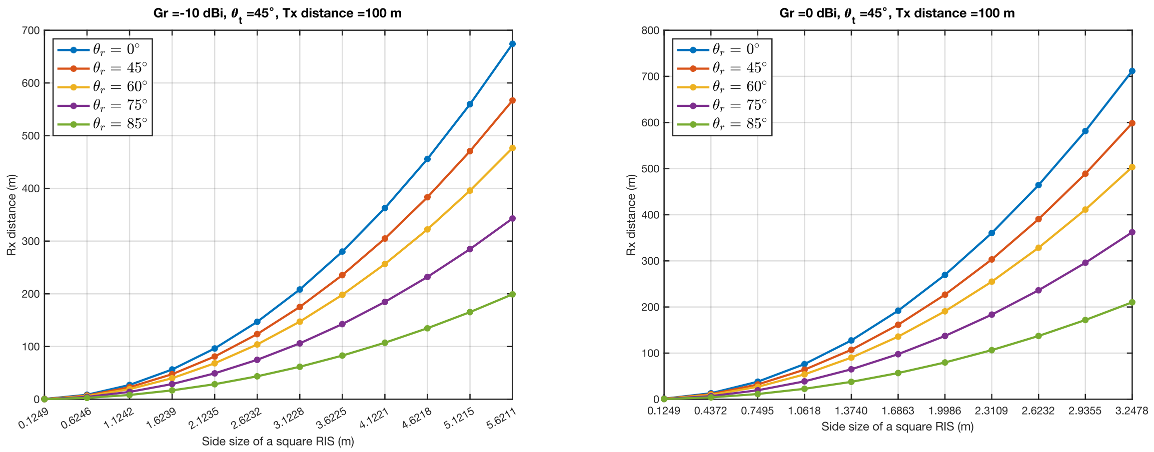
(a) G_r= -10 dBi *(b) G_r= 0 dBi*

Figure 23. Receiver distance versus RIS size, for $\theta_t = 45°$ and $d_1 = 10$ m.



(a) G_r= -10 dBi *(b) G_r= 0 dBi*

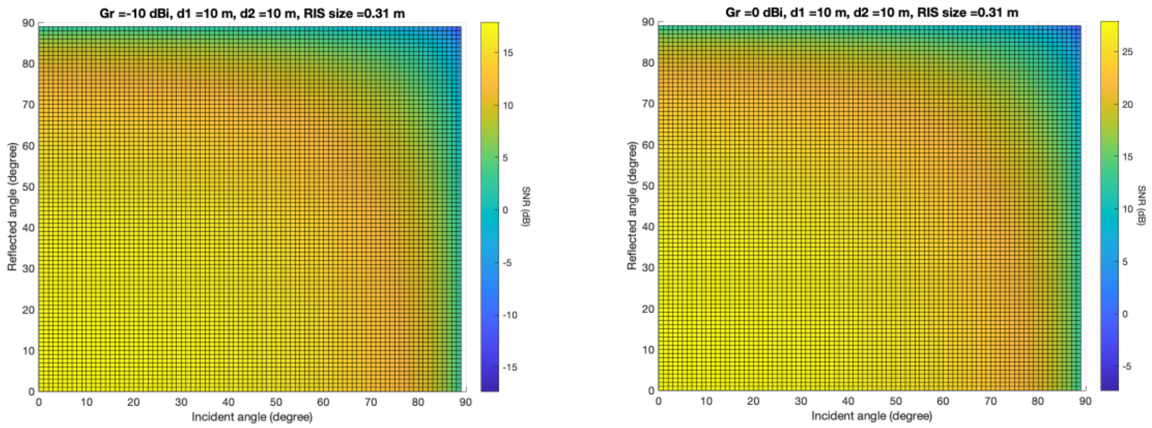
Figure 24. Receiver distance versus RIS size, for $\theta_t = 45°$ and $d_1 = 50$ m.



(a) G_r= -10 dBi (b) G_r= 0 dBi

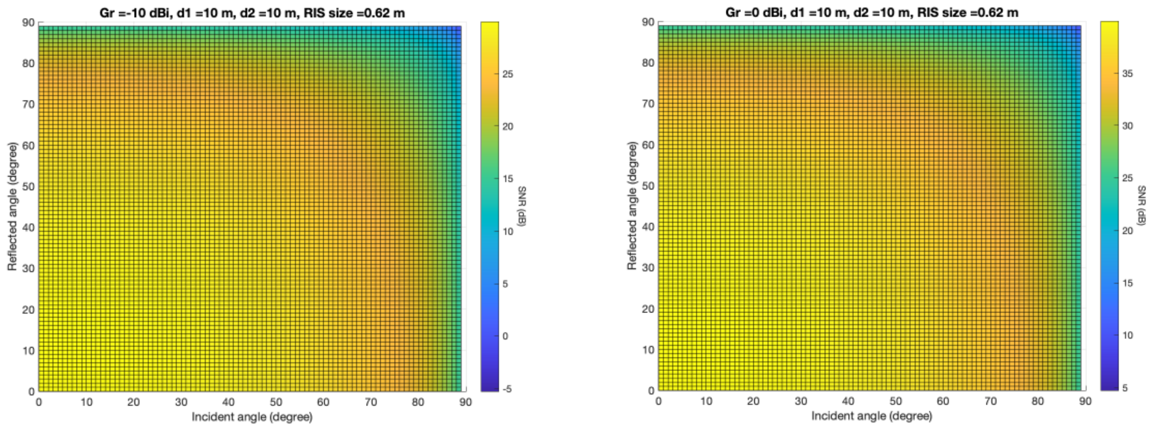
Figure 25. Receiver distance versus RIS size, for $\theta_t = 45°$ and $d_1 = 100$ m.

The SNR was obtained as a function of reflected and incident angles, considering d_1 = 10 m and d_2 = 10 m. Figure 26 and Figure 27 show the results for a RIS side length of 0.31 m (5×5) and 0.62 m (10×10), respectively, where (a) and (b) were obtained for a receiver antenna gain of G_r = -10 dBi and G_r = 0 dBi, respectively. The results show good SNR for transmitter/receiver elevation angles in the range of [0°:70°].



(a) G_r= -10 dBi (b) G_r= 0 dBi

Figure 26. SNR versus reflected and incident angles, for $d_1 = 10$ m, d_2 = 10 m, and RIS side length = 0.31 m (5×5).



(a) G_r = -10 dBi	*(b) G_r = 0 dBi*

Figure 27. SNR versus reflected and incident angles, for $d_1 = 10$ m, d_2 = 10 m, and RIS side length = 0.62 m (10×10).

Table 48 includes a summary of calculated required RIS sizes for 3 main environments, and considering two possibilities for the receiver antenna gain, namely $G_r = 0$ dBi and $G_r = -10$ dBi:

- Environment 1: Indoor home/office environment (fixing $d_1 = 10$ m and varying $d_2 = 5, 10, 20$ m)
  - RIS side length varies between 0,12 m and 0,37 m, depending on the RIS to IoT device distance (d_2) and relative angle (θ_r), considering $G_r = 0$ dBi.
- Environment 2: Indoor manufacturing/warehouse (fixing $d_1 = 50$ m and varying $d_2 = 25, 50,100$ m)
  - RIS side length varies between 0,44 m and 1,62 m, depending on the RIS to IoT device distance (d_2) and relative angle (θ_r), considering $G_r = 0$ dBi.
- Scenario 3: Outdoor smart city (fixing $d_1 = 100$ m and varying $d_2 = 100, 200, 500$ m)
  - RIS side length varies between 1,25 m and 5,06 m, depending on the RIS to IoT device distance (d_2) and relative angle (θ_r), considering $G_r = 0$ dBi.

These results provide already a more vivid picture on the size required for the RIS within different operating environments.

Table 48. Required RIS size considering different environments with $d_1 = 10$ m, 50 m, and 100 m, with varying d_2 distances, $G_r = 0$ dBi and $G_r = -10$ dBi, and $\theta_r = 0° - 85°$.

		RIS side length (m)			
		G_r = 0 dBi		G_r = -10 dBi	
d_1 (m)	d_2 (m)	θ_r=0°	θ_r=85°	θ_r=0°	θ_r=85°
(1) 10	5	0.1249	0.1874	0.1874	0.3123
	10	0.1249	0.2498	0.2498	0.4372
	20	0.1874	0.3747	0.3123	0.5621
(2) 50	25	0.4372	0.8119	0.8119	1.4365
	50	0.6246	1.2491	1.1242	1.9986
	100	0.8744	1.6239	1.5614	2.873
(3) 100	100	1.2491	2.2484	2.186	3.9972
	200	1.7488	3.1853	3.1228	5.6836
	500	2.7481	5.059	4.8716	>6

7 Conclusions

In this deliverable, we have identified scenarios and associated applications that are attractive for the concept to be developed within the SUPERIOT project. In addition, we have determined the basic requirements for each of the applications considered. The process of identifying scenarios and applications was carried out based on the distinctive qualitative, technical, and functional characteristics that the SUPERIOT concept has to offer. The work presented in this document can be seen as a key the initial step needed to define the applications that the project will consider in its development and further implementation of the four testbeds.

Three main scenarios relevant to the project were determined, namely, 1) smart tags and labels, 2) large-scale sensing and actuation, and 3) enhanced IoT communication. Each scenario in turn defined several possible applications. Each considered application was described in detail. Then, for each application a user requirements table was created, where the relevance for the application of the key SUPERIOT characteristics (e.g., requirements) were evaluated. Moreover, for each application, the expected feasibility of the requirements within the project framework was also estimated. The temporal scale was included, indicating on the timeline when the technology is expected to be mature to realize the expected applications. These requirements tables also identified the possible demonstrator where each application could possibly be demonstrated. Some of the interesting applications identified in this exhaustive analysis were not contemplated in any of the proposed project's demonstrators, either because their demanding environments were beyond the scope of the originally planned demonstrators (e.g., underwater environment, in-body applications) or because the application is too futuristic (e.g., smart medicine pills).

After connecting the applications to each possible planned demonstrator(s), a more detailed analysis of requirements was performed per demonstrator. Due to their different and specific challenges, distinct approaches were used for each demonstrator.

In demonstrators 1 and 2 we defined some examples of use cases that helped us define ranges of values for functional requirements. The target of estimating these values is not in any way limiting the development of the technology, they should be seen as mere guidance for the rest of the project.

For demonstrator 3, a different approach was used. The set of features to be applied on a fully-printed node is severely limited, due to the constraints of the currently available and developing printed components technology. For this demonstrator, the use cases to be demonstrated will be defined based on what the features we are able to achieve during the project. With that in mind, user requirements were drafted based on what is possibly expected in a user level for a fully-printed node.

To guide the development of the RIS for demonstrator 4, simulations of the link budget were performed based on the possible values for the RIS parameters.

The scenarios, applications and requirements presented in this document help the partners create a common vision for the technology that is going to be developed within the SUPERIOT project. Scenarios, applications, and corresponding requirements will be iteratively refined and revised throughout the lifetime of the project to ensure SUPERIOT is able to produce relevant and viable technology.

8 Bibliography

[1] Cisco Annual Internet Report (2018–2023) White Paper, available at https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html

[2] P. A. Laplante and N. Laplante, "The Internet of Things in Healthcare: Potential Applications and Challenges," in IT Professional, vol. 18, no. 3, pp. 2-4, May-June 2016, doi: 10.1109/MITP.2016.42.

[3] H. Zhu et al., "Smart Healthcare in the Era of Internet-of-Things," in IEEE Consumer Electronics Magazine, vol. 8, no. 5, pp. 26-30, 1 Sept. 2019, doi: 10.1109/MCE.2019.2923929.

[4] M. N. Bhuiyan, M. M. Rahman, M. M. Billah and D. Saha, "Internet of Things (IoT): A Review of Its Enabling Technologies in Healthcare Applications, Standards Protocols, Security, and Market Opportunities," in IEEE Internet of Things Journal, vol. 8, no. 13, pp. 10474-10498, 1 July1, 2021.

[5] N. Zhu et al., "Bridging e-Health and the Internet of Things: The SPHERE Project," in IEEE Intelligent Systems, vol. 30, no. 4, pp. 39-46, July-Aug. 2015, doi: 10.1109/MIS.2015.57.

[6] M. Antić and I. Papp, "Smart Home Integration with External IoT Device Platforms and Services," in IEEE Consumer Electronics Magazine, vol. 10, no. 6, pp. 69-75, 1 Nov. 2021, doi: 10.1109/MCE.2020.3042008.

[7] O. Barker, "Realizing the Promise of the Internet of Things in Smart Buildings," in Computer, vol. 53, no. 2, pp. 76-79, Feb. 2020, doi: 10.1109/MC.2019.2952419.

[8] K. Xu, Y. Wan and G. Xue, "Powering Smart Homes with Information-Centric Networking," in IEEE Communications Magazine, vol. 57, no. 6, pp. 40-46, June 2019, doi: 10.1109/MCOM.2019.1800732.

[9] B. Y. Sovetov, T. M. Tatarnikova and V. V. Cehanovsky, "Physical Access Control System for the Premises using the Internet of Things Technology," 2020 9th Mediterranean Conference on Embedded Computing (MECO), 2020, pp. 1-4, doi: 10.1109/MECO49872.2020.9134107

[10] N. Saeed, T. Y. Al-Naffouri and M. -S. Alouini, "Around the World of IoT/Climate Monitoring Using Internet of X-Things," in IEEE Internet of Things Magazine, vol. 3, no. 2, pp. 82-83, June 2020, doi: 10.1109/MIOT.2020.9125423

[11] H. A. Khattak, H. Farman, B. Jan and I. U. Din, "Toward Integrating Vehicular Clouds with IoT for Smart City Services," in IEEE Network, vol. 33, no. 2, pp. 65-71, March/April 2019, doi: 10.1109/MNET.2019.1800236.

[12] C. Wu, Z. Liu, D. Zhang, T. Yoshinaga and Y. Ji, "Spatial Intelligence toward Trustworthy Vehicular IoT," in IEEE Communications Magazine, vol. 56, no. 10, pp. 22-27, OCTOBER 2018, doi: 10.1109/MCOM.2018.1800089.

[13] M. Humayun, N. Jhanjhi, B. Hamid and G. Ahmed, "Emerging Smart Logistics and Transportation Using IoT and Blockchain," in IEEE Internet of Things Magazine, vol. 3, no. 2, pp. 58-62, June 2020, doi: 10.1109/IOTM.0001.1900097.

[14] A. Pal and K. Kant, "IoT-Based Sensing and Communications Infrastructure for the Fresh Food Supply Chain," in Computer, vol. 51, no. 2, pp. 76-80, February 2018, doi: 10.1109/MC.2018.1451665.

[15] V. Shvaichenko, Y. Onikienko, V. Bakiko and O. Pereverziev, "The Concept of Integrating the Fashion Industry into the Entertainment Industry on the basis of the Internet of Things," 2019 3rd International Conference on Advanced Information and Communications Technologies (AICT), 2019, pp. 298-301

[16] S. E. Collier, "The Emerging Enernet: Convergence of the Smart Grid with the Internet of Things," in IEEE Industry Applications Magazine, vol. 23, no. 2, pp. 12-16, March-April 2017, doi: 10.1109/MIAS.2016.2600737.

[17] B. Ahlgren, M. Hidell and E. C. -. Ngai, "Internet of Things for Smart Cities: Interoperability and Open Data," in IEEE Internet Computing, vol. 20, no. 6, pp. 52-56, Nov.-Dec. 2016, doi: 10.1109/MIC.2016.124.

[18] A. A. Brincat, F. Pacifici and F. Mazzola, "IoT as a Service for Smart Cities and Nations," in IEEE Internet of Things Magazine, vol. 2, no. 1, pp. 28-31, March 2019, doi: 10.1109/IOTM.2019.1900014.

[19] M. Wollschlaeger, T. Sauter and J. Jasperneite, "The Future of Industrial Communication: Automation Networks in the Era of the Internet of Things and Industry 4.0," in IEEE Industrial Electronics Magazine, vol. 11, no. 1, pp. 17-27, March 2017, doi: 10.1109/MIE.2017.2649104.

[20] F. Griffiths and M. Ooi, "The fourth industrial revolution - Industry 4.0 and IoT [Trends in Future I&M]," in IEEE Instrumentation & Measurement Magazine, vol. 21, no. 6, pp. 29-43, December 2018, doi: 10.1109/MIM.2018.8573590.

[21] J. Ruan et al., "Agriculture IoT: Emerging Trends, Cooperation Networks, and Outlook," in IEEE Wireless Communications, vol. 26, no. 6, pp. 56-63, December 2019, doi: 10.1109/MWC.001.1900096.

[22] C. Brewster, I. Roussaki, N. Kalatzis, K. Doolin and K. Ellis, "IoT in Agriculture: Designing a Europe-Wide Large-Scale Pilot," in IEEE Communications Magazine, vol. 55, no. 9, pp. 26-33, Sept. 2017, doi: 10.1109/MCOM.2017.1600528.

[23] F. O'Donncha and J. Grant, "Precision Aquaculture," in IEEE Internet of Things Magazine, vol. 2, no. 4, pp. 26-30, December 2019, doi: 10.1109/IOTM.0001.1900033.

[24] Ynvisible, D0432G02V01 – Seven Segment E-Paper Display Datasheet, online: https://assets.website-files.com/5f7f21e12602d912658dce12/62207f04e89fc72369fa582a_D0432G02V01-V1.0.pdf

[25] Ynvisible, D0430G02V01 – Signed Double Digit E-Paper Display, online: https://assets.website-files.com/5f7f21e12602d912658dce12/62207f05740c66df99b65e07_D0430G02V01-V1.0.pdf

[26] Ynvisible, D0431G02V01 – Bar Graph E-Paper Display, online: https://assets.website-files.com/5f7f21e12602d912658dce12/62207f059a97570924e24003_D0431G02V01-V1.0.pdf

[27] W. Tang et al., "Wireless Communications with Reconfigurable Intelligent Surface: Path Loss Modeling and Experimental Measurement," in IEEE Transactions on Wireless Communications, vol. 20, no. 1, pp. 421-439, Jan. 2021, doi: 10.1109/TWC.2020.3024887.

[28] H. Yang et al., "A Study of Phase Quantization Effects for Reconfigurable Reflectarray Antennas," in IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 302-305, 2017, doi: 10.1109/LAWP.2016.2574118.

[29] PERVASIVE DISPLAYS, 2.71″ E-ink displays, online: https://www.pervasivedisplays.com/product/2-71-e-ink-displays/

[30] PERVASIVE DISPLAYS, 4.37″ E-ink displays, online: https://www.pervasivedisplays.com/product/4-37-e-ink-displays/#ptab-2

9 List of figures

10 List of tables

11 List of contributors

Contributors	**Short name**	**Country**
OULUN YLIOPISTO	UOULU	Finland
INESC TEC - INSTITUTO DE ENGENHARIADE SISTEMAS E COMPUTADORES, TECNOLOGIA E CIENCIA	INESC TEC	Portugal
TEKNOLOGIAN TUTKIMUSKESKUS VTT OY	VTT	Finland
NOVA ID FCT - ASSOCIACAO PARA A INOVACAO E DESENVOLVIMENTO DA FCT	NOVA.id.FCT	Portugal
STICHTING IMEC NEDERLAND	IMEC-NL	Netherlands
LIGHTBEE SL	LIGHTBEE SL	Spain
MPICOSYS - EMBEDDED PICO SYSTEMS SPZOO	MPICOSYS	Poland
KATHOLIEKE UNIVERSITEIT LEUVEN	KU Leuven	Belgium
WAVECOM SOLUCOES RADIO SA	WAVECOM	Portugal
UNIVERSITY OF BRISTOL	U of Bristol	United Kingdom

12 Appendix 1

Form for applications gathering

SUPERIOT | Kick-off Meeting Oulu 12-13.01.2023 | UNIVERSITY OF OULU

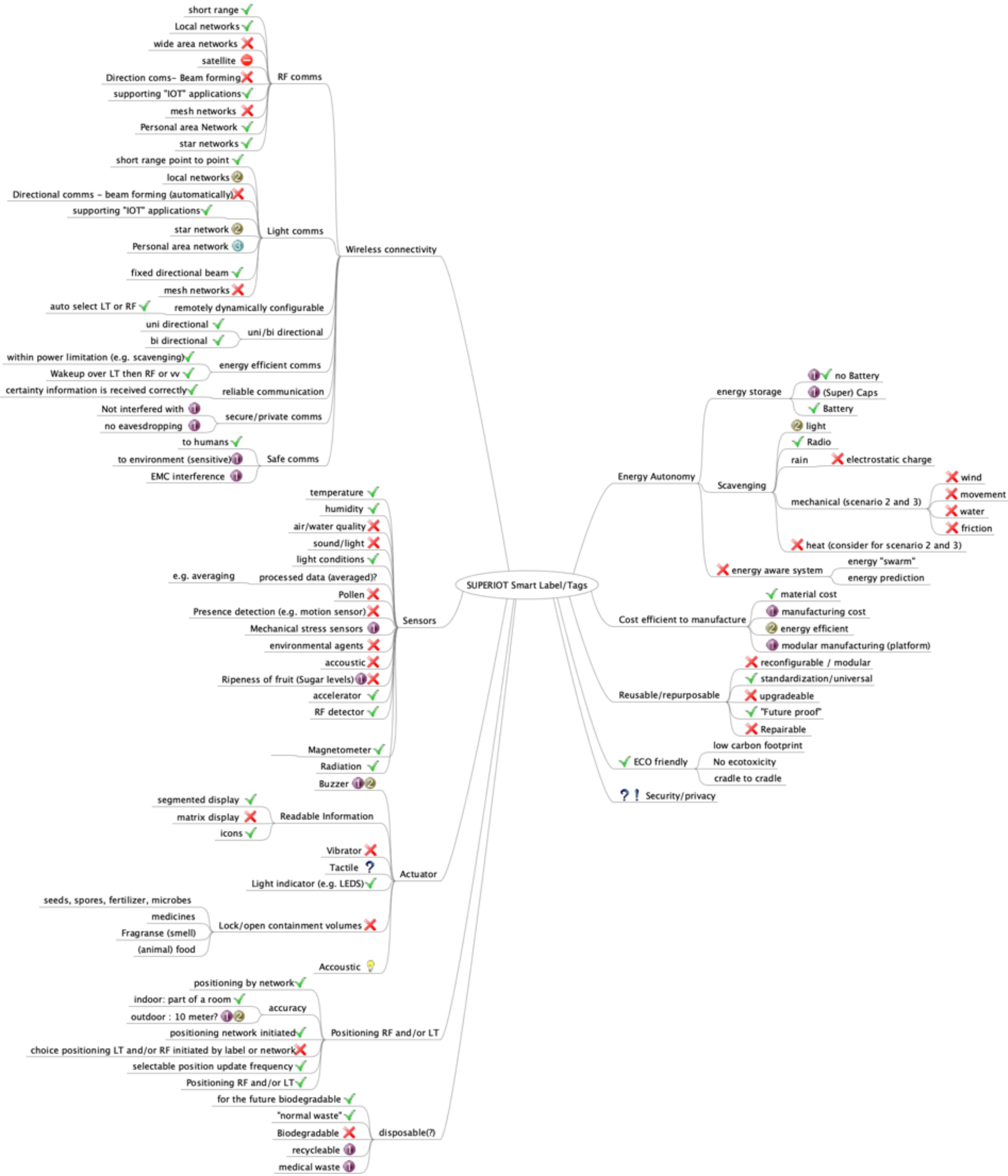
Organization: WP1: Use case/Application/Environment identification

Use case/ Application /Environment (simple name or designation)	
Definition (what?)	
Benefits (why?) **SUPERIOT advantages** (technologies involved)	
Other	

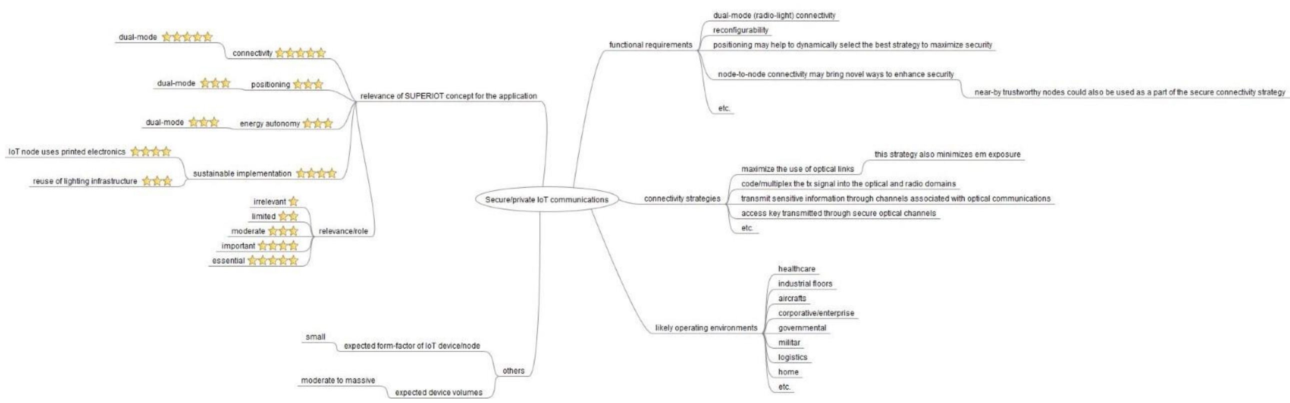
13 Appendix 2

Mind maps for requirements

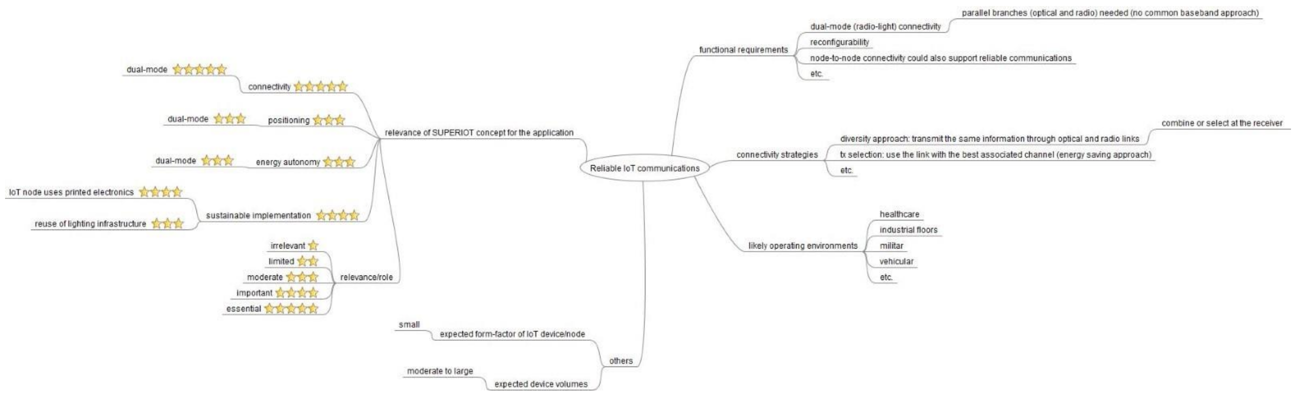
In order to identify, understand, define and determine requirements of the scenarios and associated applications, mind maps were developed. In this Appendix, we include these mind maps for reference.



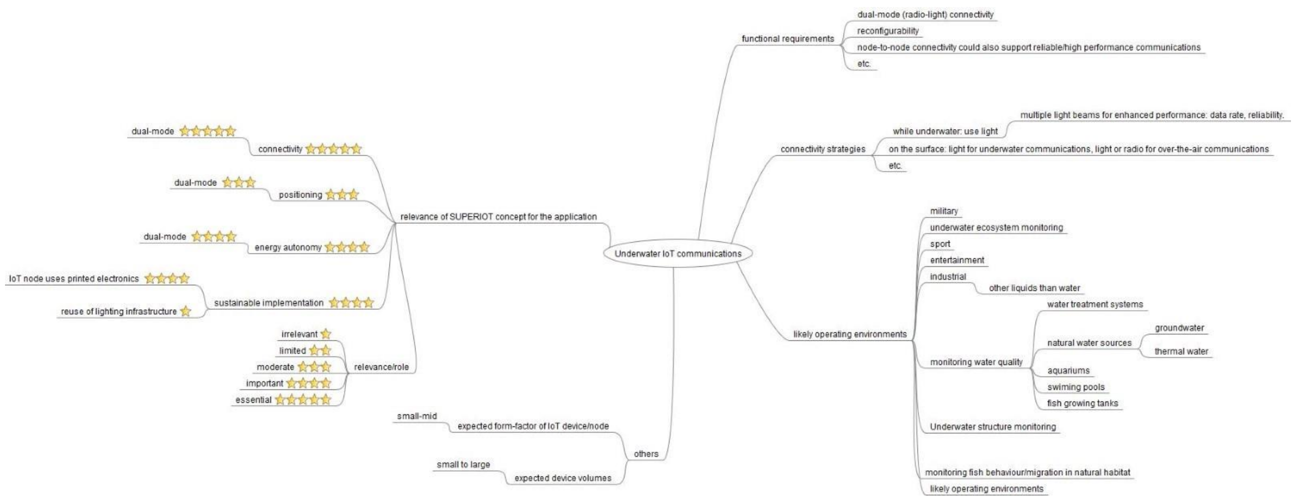
Mind map of Scenario 1 – Smart tags and labels



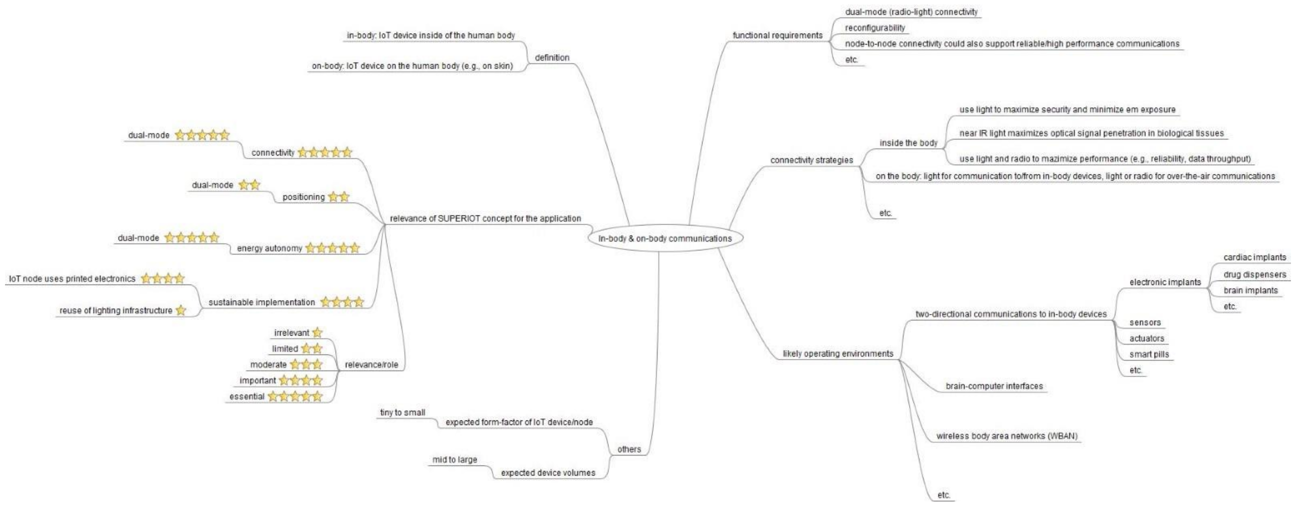
Mind map of scenario 3, application 3.1 - Secure and private IoT communication



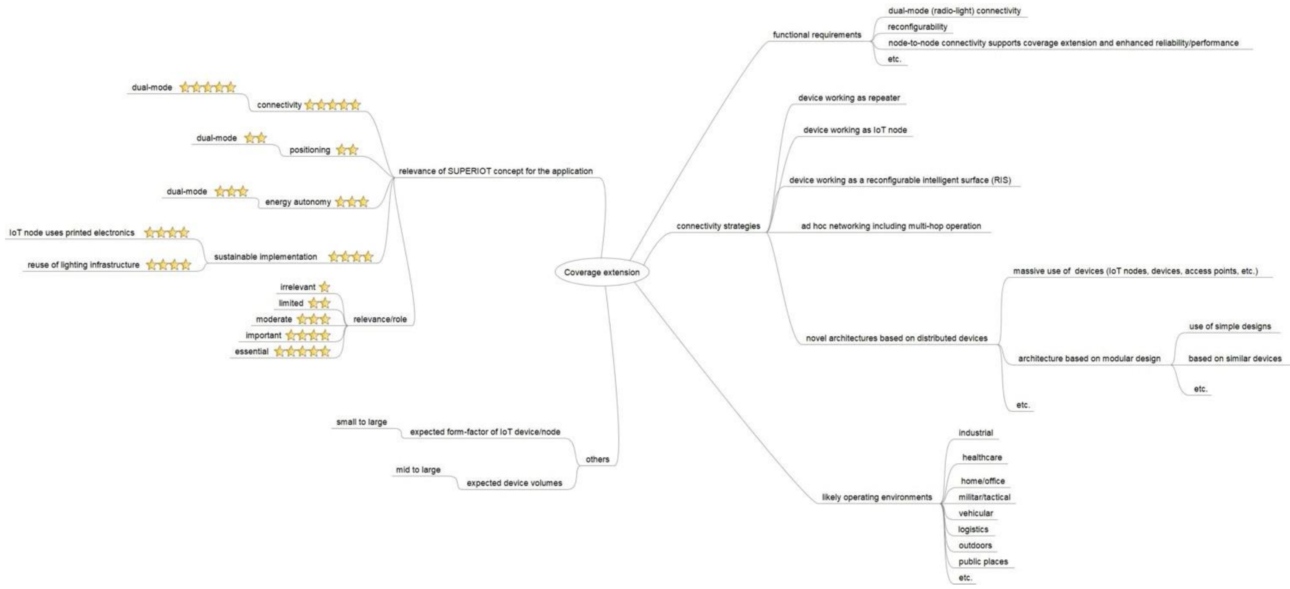
Mind map of scenario 3, application 3.2 - Reliable IoT communication



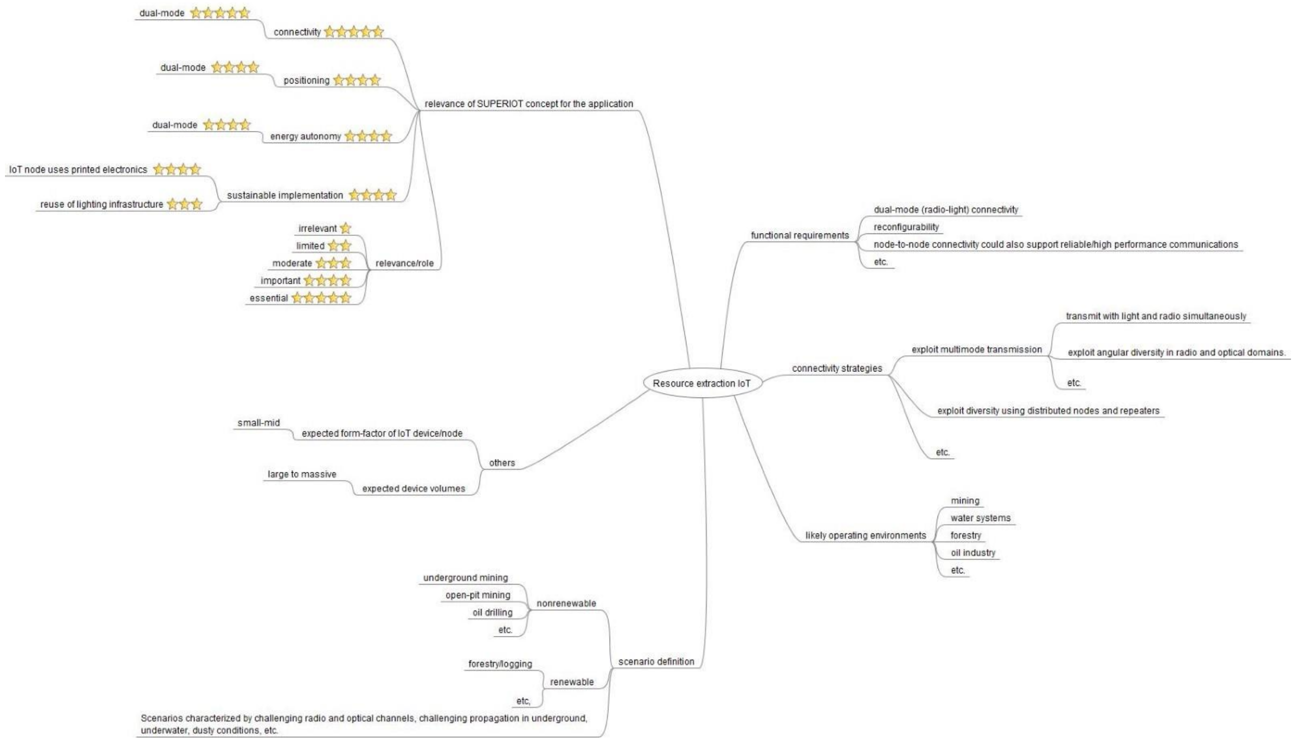
Mind map of scenario 3, application 3.3 - Underwater IoT communication



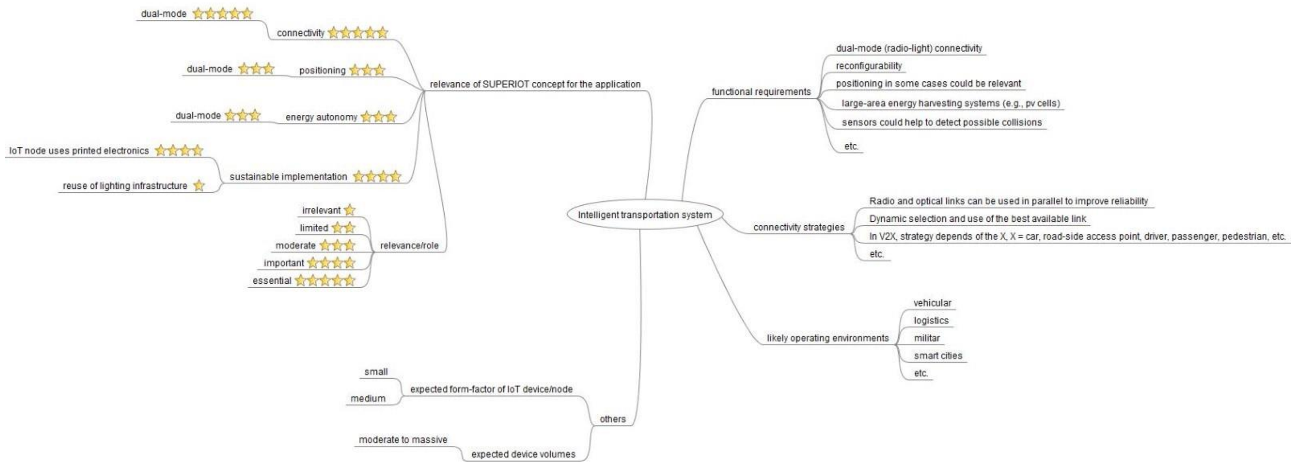
Mind map of scenario 3, application 3.4 - In-body and on-body communication



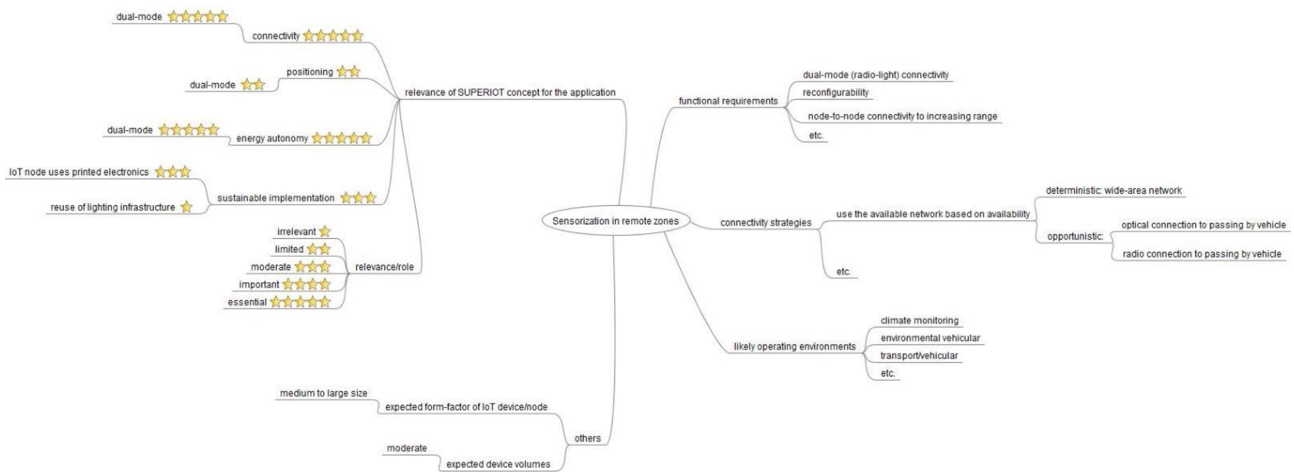
Mind map of scenario 3, application 3.5 - Coverage extension with large-area IoT nodes



Mind map of scenario 3, application 3.6 - Resource extraction supported by IoT communication



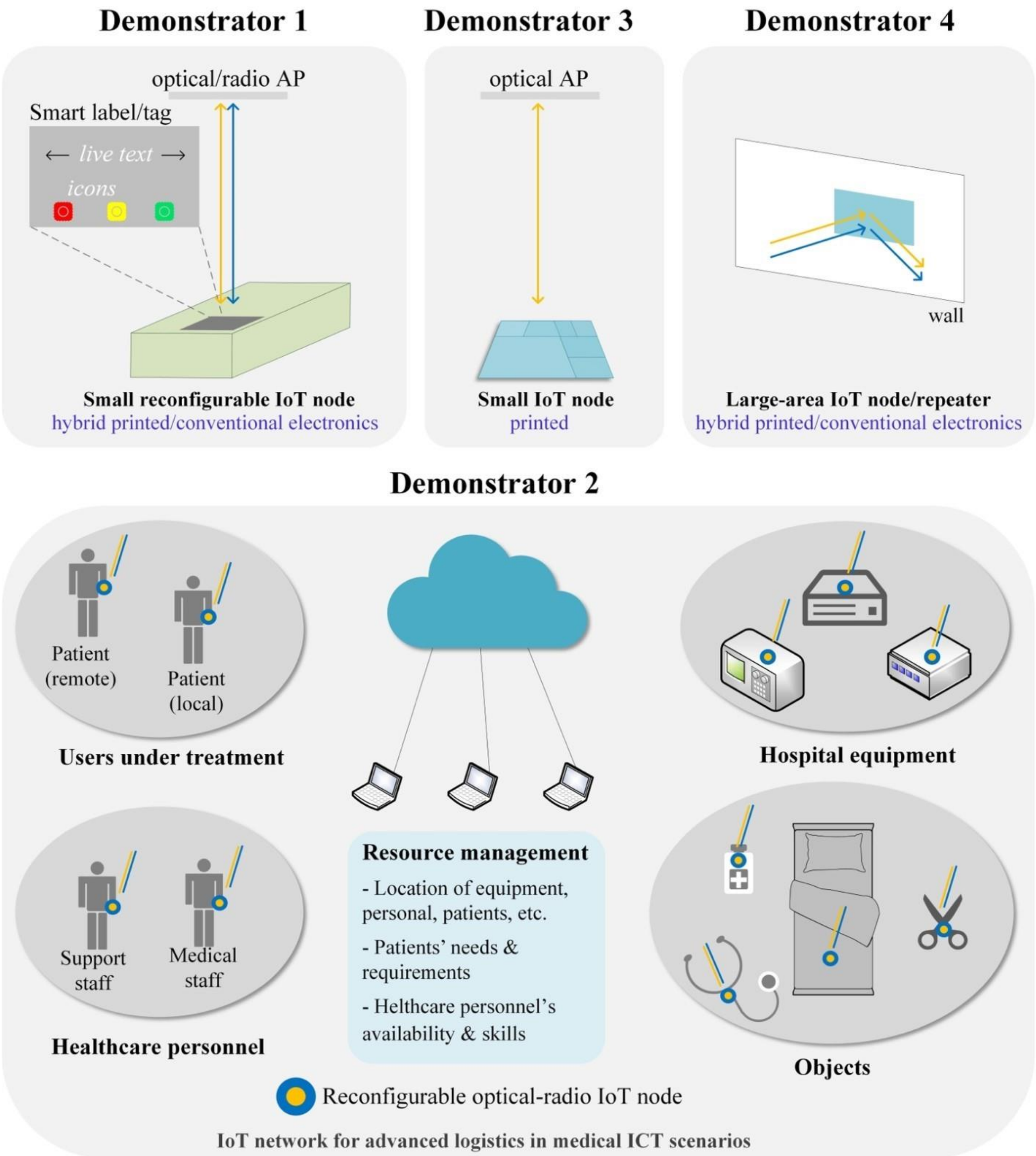
Mind map of scenario 3, application 3.7 - Intelligent transportation systems



Mind map of scenario 3, application 3.8 - Sensorization and IoT communication in remote zones

14 Appendix 3

Planned demonstrators in the SUPERIOT project



The four demonstrators planned in the SUPERIOT project

15 Appendix 4

References for current and future functional requirements

Actuators

The actuators have an important share in the IoT node's energy consumption. Among the actuator components, we distinguish e-paper displays. The e-paper display can be implemented in the form of a non-printed or printed component. The energy consumption of the E-paper displays with built-in silicon-based elements has been measured as 9.1 mJ for 2.71" monochrome display [29] of resolution 264 px per 176 px. For 4.37" fast update monochrome display [30] of resolution 480 px per 176 px, this consumption has been measured as 9.9 mJ. These energy consumptions have been measured per one refresh of the display content and energy consumption occurs only during changing the displayed content.

For simple content, depending on the use case, the seven-segment E-paper displays can be considered. This kind of E-paper displays can be implemented as a printed component without built-in silicon-based elements. The seven-segment E-paper display consists of one digit with dimensions of 9 mm per 23.6 mm. It consumes 0.73 mJ per one refresh [24]. For the double digits version, the energy consumption is 1.56 mJ [25]. Similar consumption of 1.53 mJ is reported for seven-segment bar graph E-paper display [26]. All of these printed displays require a short refresh pulse every 2 minutes [24], [25], [26]. This short refresh pulse requirement can induce excessive energy consumption compared to the above mentioned 2.71" and 4.37" displays that do not need the refresh pulses. Similarly for more complex content and need of actuating more digits, each consuming 0.73 mJ.

Depending on applied technology: the energy consumption of the IoT node due the e-paper actuating can be within 10 mJ for a decent size and resolution dot-matrix displays for unrestricted refresh period; or the energy consumption can be within 0.73 mJ for the seven-segment E-paper display for one digit refresh.

To provide this 10 mJ of energy only for the above-mentioned decent size and resolution dot-matrix display, assuming that the display operates discharging the capacitor(s) from 3.3 V to the display minimum operating voltage of 2.3 V, a 3.6 mF of capacitance is needed. Assuming a margin of error and losses, it could be at least 5 mF per one refresh.

For the seven-segment display, consuming 0.73 mJ of energy, assuming discharging the capacitor(s) from 3.3 V to 1.8 V, omitting the LDO losses, there is needed 0.2 mF of capacitance per one digit refresh. The LDO (or another voltage converter) is needed due to the seven-segment display minimum and maximum voltages: 1.0 V and 1.55 V, respectively. Assuming LDO efficiency of 60%, it could be at least 0,33 mF of capacitance per one digit refresh. For the signed double-digit E-paper display (1.56 mJ consumption) and bar graph E-paper display (1.53 mJ consumption), assuming the same LDO efficiency, it could be ca. 0.7 mF.

Sensors

9.10.2023 16

Value ranges to measure physiological data

Parameter	*Range of Parameter*	*Signal Frequency*
ECG signal	0.5-4mV	0.01 – 250 Hz
Respiratory rate	2-50breaths/min	0.1 –10 Hz
Blood Pressure (BP)	10-400mm Hg	0-50 Hz
EEG	3µV-300µV	0.5-60 Hz
Body Temperature	32-40 °C	0 - 0.1Hz
EMG(Electromyogram)	10µV-15mV	10-5000 Hz
GSR(Galvanic Skin Reflex)	30µV-3mV	0.03-20 Hz

Physiological Signal	*Parameter range*	*Maximum Frequency (Hz)*	*Sample Interarrival time (sec)*	*Payload /sample(bits)*	*Required data rate (kbs)*
Blood flow	1-300ml/s	20	0.025	12	0.48
ECG signal	0.5-4mV	250	0.002	12	6.0
Respiratory rate	2-50breaths/min	10	0.05	12	0.24
Blood Pressure (Direct Arterial)	10-400mm Hg	50	0.01	12	1.2
Blood pH	6.8-7.8pH units	2	0.25	12	.048
Nerve Potentials	0.01-3mV	10,000	5E-06	12	2400
Body Temperature	32-40 °C	0.1	5	12	.0024

typically, very low data rate requirements

Source: J. Khan, M. Yuce, "Wireless body area networks (WBAN) for medical applications", In: New developments in biomedical engineering, Intechopen, 2010. DOI: 10.5772/7598

CWC CENTRE FOR WIRELESS COMMUNICATIONS University of Oulu
UNIVERSITY of OULU OULUN YLIOPISTO

Value ranges to measure physiological data

Application type	Sensor node	Data rate	Duty cycle (per device) % per time	Power consumption	QoS (sensitive to latency)	Privacy
In-body application	Glucose sensor	Few kbps	<1%	Extremely high	Yes	High
	Pacemaker	Few kbps	<1%	Low	Yes	High
	Endoscope capsule	>2 Mbps	<50%	Low	Yes	Medium
On-body medical application	ECG	3 kbps	<10%	Low	Yes	High
	SpO2	32 kbps	<1%	Low	Yes	High
	Blood pressure	<10 bps	<1%	High	Yes	Medium
On-body non-medical application	Music for headsets	1.4 Mbps	High	Relatively high	Yes	Low
	Forgotten things monitor	256 kbps	Medium	Low	No	Low
	Social networking	<200 kbps	<1%	Low	No	High

QoS: Quality of Service; ECG: electrocardiogram.

video stream is provided

R.A. Khan, A.-S. Khan Pathan, "The state-of-the-art wireless body area sensor networks: A survey", International Journal of distributed Sensor networks, Vol 14(4), 2018.

CWC CENTRE FOR WIRELESS COMMUNICATIONS University of Oulu
UNIVERSITY of OULU OULUN YLIOPISTO